

Proceedings of Previous Easter Schools in Agricultural Science, published by Butterworths, London

- *SOIL ZOOLOGY Edited by D. K. McL. Kevan (1955)
- *THE GROWTH OF LEAVES Edited by F. L. Milthorpe (1956)
- *CONTROL OF THE PLANT ENVIRONMENT Edited by J. P. Hudson (1957)
- *NUTRITION OF THE LEGUMES Edited by E. G. Hallsworth (1958)
- *THE MEASUREMENT OF GRASSLAND PRODUCTIVITY Edited by J. D. Ivins (1959)
- *DIGESTIVE PHYSIOLOGY AND NUTRITION OF THE RUMINANT Edited by D. Lewis (1960)
- *NUTRITION OF PIGS AND POULTRY Edited by J. T. Morgan and D. Lewis (1961)
- *ANTIBIOTICS IN AGRICULTURE Edited by M. Woodbine (1962)
- *THE GROWTH OF THE POTATO Edited by J. D. Ivins and F. L. Milthorpe (1963)
- *EXPERIMENTAL PEDOLOGY Edited by E. G. Hallsworth and D. V. Crawford (1964)
- *THE GROWTH OF CEREALS AND GRASSES Edited by F. L. Milthorpe and J. D. Ivins (1965)
- *REPRODUCTION IN THE FEMALE MAMMAL Edited by G. E. Lamming and E. C. Amoroso (1967)
- *GROWTH AND DEVELOPMENT OF MAMMALS Edited by G. A. Lodge and G. E. Lamming (1968)
- *ROOT GROWTH Edited by W. J. Whittington (1968)
- *PROTEINS AS HUMAN FOOD Edited by R. A. Lawrie (1970)
- *LACTATION Edited by I. R. Falconer (1971)
- *PIG PRODUCTION Edited by D. J. A. Cole (1972)
- *SEED ECOLOGY Edited by W. Heydecker (1973)
- HEAT LOSS FROM ANIMALS AND MAN: ASSESSMENT AND CONTROL Edited by J. L. Monteith and L. E. Mount (1974)
- *MEAT Edited by D. J. A. Cole and R. A. Lawrie (1975)
- *PRINCIPLES OF CATTLE PRODUCTION Edited by Henry Swan and W. H. Broster (1976)
- *LIGHT AND PLANT DEVELOPMENT Edited by H. Smith (1976)
- PLANT PROTEINS Edited by G. Norton (1977)
- ANTIBIOTICS AND ANTIBIOSIS IN AGRICULTURE Edited by M. Woodbine (1977)
- CONTROL OF OVULATION Edited by D. B. Crighton, N. B. Haynes, G. R. Foxcroft and G. E. Lamming (1978)
- POLYSACCHARIDES IN FOOD Edited by J. M. V. Blanshard and J. R. Mitchell (1979)
- SEED PRODUCTION Edited by P. D. Hebblethwaite (1980)
- PROTEIN DEPOSITION IN ANIMALS Edited by P. J. Buttery and D. B. Lindsay (1981)
- PHYSIOLOGICAL PROCESSES LIMITING PLANT PRODUCTIVITY Edited by C. Johnson (1981)
- ENVIRONMENTAL ASPECTS OF HOUSING FOR ANIMAL PRODUCTION Edited by J. A. Clark (1981)
- EFFECTS OF GASEOUS AIR POLLUTION IN AGRICULTURE AND HORTICULTURE Edited by M. H. Unsworth and D. P. Ormrod (1982)
- CHEMICAL MANIPULATION OF CROP GROWTH AND DEVELOPMENT Edited by J. S. McLaren (1982)
- CONTROL OF PIG REPRODUCTION Edited by D. J. A. Cole and G. R. Foxcroft (1982)
- SHEEP PRODUCTION Edited by W. Haresign (1983)
- UPGRADING WASTE FOR FEEDS AND FOOD Edited by D. A. Ledward, A. J. Taylor and R. A. Lawrie (1983)
- FATS IN ANIMAL NUTRITION Edited by J. Wiseman (1984)
- IMMUNOLOGICAL ASPECTS OF REPRODUCTION IN MAMMALS Edited by D. B. Crighton (1984)
- ETHYLENE AND PLANT DEVELOPMENT Edited by J. A. Roberts and G. A. Tucker (1985)
- THE PEA CROP Edited by P. D. Hebblethwaite, M. C. Heath and T. C. K. Dawkins (1985)
- PLANT TISSUE CULTURE AND ITS AGRICULTURAL APPLICATIONS Edited by Lyndsey A. Withers and P. G. Alderson (1986)
- CONTROL AND MANIPULATION OF ANIMAL GROWTH Edited by P. J. Buttery, D. B. Lindsay and N. N. Haynes (1986)

**The titles are now out of print but are available in microfiche editions*

VISIT...

LANZAROTE
Caliente.COM

Computer Applications in Agricultural Environments

J.A. CLARK

University of Nottingham School of Agriculture

K. GREGSON

University of Nottingham School of Agriculture

R.A. SAFFELL

Campbell Scientific Ltd

BUTTERWORTHS

London Boston Durban Singapore Sydney Toronto Wellington

All rights reserved. No part of this publication may be reproduced or transmitted in any form or by any means, including photocopying and recording, without the written permission of the copyright holder, application for which should be addressed to the Publishers. Such written permission must also be obtained before any part of this publication is stored in a retrieval system of any nature.

This book is sold subject to the Standard Conditions of Sale of Net Books and may not be re-sold in the UK below the net price given by the Publishers in their current price list.

First published 1987

© The several contributors named in the list of contents 1987

British Library Cataloguing in Publication Data

Computer applications in agricultural environments

1. Agriculture — Data processing

I. Clark, J.A., 1946— II. Gregson, K.

III. Saffell, R.A.

338.1'6 S494.5.D3

ISBN 0-407-00429-7

Library of Congress Cataloging in Publication Data

Computer applications in agricultural environments.

Proceedings of the 42nd Nottingham Easter School.

Bibliography: p.

Includes index.

1. Greenhouses—Environmental engineering—Data processing—Congresses. 2. Greenhouses—Climate—Data processing—Congresses. 3. Animal housing—Environmental engineering—Data processing—Congresses. 4. Animal housing—Climate—Data processing—Congresses. 5. Food industry and trade—Data processing—Congresses.

I. Clark, J.A. (Jeremy Austin), 1938—

II. Gregson, K. III. Saffell, R.A.

SB416.C65 1986 630 86-17121

ISBN 0-407-00429-7

PREFACE

The development of the microprocessor has promoted the use of computational techniques in an expanding variety of applications in measurement and control. The initial advances in computer control were confined to engineering and related disciplines, and traditionally the development of computing has occurred within the pure science and engineering departments of universities and colleges.

The application of computer skills to agriculture has been relatively infrequent, and until recently has been confined mainly to the economic and managerial aspects of the farming and food industries. More recently, with the advent of large scale integrated circuits and the consequent low cost and portability of both computers and the necessary instrumentation, it has been possible to exploit the power of the microprocessor outside the laboratory. This has produced a growing awareness that many of the traditional uses of environmental control mechanisms could benefit from the application of computers. In particular, the control of the microclimate in greenhouses and animal houses and for food storage and processing have become prime areas where the power of the computer may be of benefit.

The aim of this Easter School was to promote this awareness and to provide a forum where experiences of the application of computer techniques which are common to many disciplines, but which have been developed and used in a wide variety of applications, could be shared.

The proceedings of the Easter School may be broken into three main areas. The first section introduces the theoretical aspects of computer control. This is followed by examples of applications to the control of the environment of plants in greenhouses, grain driers, etc. Consideration is also given to the problems encountered in the food processing industry, illustrating that many of the problems encountered are not specific to one area of application. The remaining topics of the conference were in the areas of environmental control for animal housing and data logging, in which a wide range of computer applications were introduced.

A review of the titles and authors of the twenty or so papers presented will reveal the diversity of the applications and disciplines represented at the conference. This helped to sustain the discussions both within and outside the formal meetings. The poster sessions were also a source of many ideas and gave the opportunity for exchange of opinions.

ACKNOWLEDGEMENTS

We would like to express our thanks to all who presented papers at the meeting and to those delegates who prepared and presented posters at the evening sessions.

We are also grateful to the Vice-Chancellor of the University, Professor B.C.L. Weedon, who opened the meeting and extended a welcome to the many overseas delegates. Thanks are also due to the chairmen of the various sessions, whose skill ensured good time-keeping throughout the conference.

May we also extend our thanks to Mrs Tricia Falkener Smith who ensured the smooth running of the meeting and to Mrs Claire Saffell who gave invaluable help during the conference.

The University of Nottingham School of Agriculture is also grateful to the following companies who provided financial assistance towards the expenses of the School:

Seltek Instruments Ltd
Delta-T-Devices Ltd
Grant Instruments Ltd
The Analytical Development Company Ltd
Christie Electronics Ltd
Vector Instruments
Decagon Devices, Inc.
Vaisala UK
Lintronic Ltd
Didcot Instrument Company Ltd
Skye Instruments Ltd
Fisons Environment Equipment Ltd

ANALYSIS AND SYNTHESIS OF GREENHOUSE CLIMATE CONTROLLERS

A.J. UDINK TEN CATE

Agricultural University, Wageningen, Netherlands

Introduction

In Western Europe the popularity of computers for the control of greenhouses is still increasing. In the Netherlands, for example, computers are found in every large commercial holding, with about 4000 units in operation. The computer performs tasks like climate, boiler and irrigation control. The best known application is climate control (temperature, humidity, CO₂, artificial lighting). Typically, in climate control computer algorithms perform the same functions as conventional electronic controllers. The main improvements are found in data logging, the ways in which the set point of a controlled variable can be changed, reproducibility of the control signals over long periods (no ill-tuned potentiometers!) and alarm functions. Also, if a meteorological station is coupled to the computer some decisions on set point schedules can be made automatically.

Recent trends to energy conservation, as well as the integration of administrative management and climate control, provide a strong stimulus for improvement of the quality and accuracy of the climate control itself. A computer provides an excellent tool to employ improved algorithms and new control methods. For analysis and design purposes there is a great need for models of the greenhouse climate that are reliable from the control point of view. Also, because of the difficulty of performing experiments in greenhouses in order to compare the relative merits of various methods, modelling of the greenhouse climate has become of great importance.

In contrast to the limited availability of control models of the greenhouse climate, physical models are widely available. These models are typically of the aggregated type, where the thermodynamic properties of the greenhouse structure, the soil and the crop are entered as parameters in a model based on heat and mass transfer theory. The model can be of the steady state type (e.g. Businger, 1963; Garzoli and Blackwell, 1973; Kimball, 1973), or can also account for energy storage in the greenhouse (notably in the soil) (e.g. Takakura, Jordan and Boyd, 1971; Van Bavel, Damagnez and Sadler, 1981; Bot, 1983). In principle, dynamic physical models could be employed for control. However, in control the main interest is in the effect of small perturbations from the nominal working point. As a rule the perturbations are of relatively high frequency compared with the dominant model time scale: the working point changes only slowly. So far, physical models have been used only in simulation runs with slowly varying (low-frequency) input signals,

2 Analysis and synthesis of greenhouse climate controllers

whereas the control models must have accurate high-frequency responses with less stringent requirements on low frequency responses (Udink ten Cate, 1983).

A major reason for the slow development of control models is the relative complexity of the greenhouse climate. Even for a model of the air temperature inside a greenhouse, at least four input signals are employed — outside air temperature, solar radiation, heating system temperature and ventilation rate. This makes a validation of the model cumbersome. The techniques used in the validation are time-series analysis (for parameter estimation) and frequency domain analysis (using Fast Fourier Transform and anti-causal filtering techniques). Also, techniques like correlation and power spectrum analysis, which are based on linear modelling, are used. The above techniques have only become available quite recently in interactive program packages on minicomputers. The required amount of data collection is only made possible by using data loggers with sufficient data storage facilities and by the ability to generate test input signals with the required frequency characteristics. This all explains why control models in greenhouses have emerged only recently (Hashimoto, Morimoto and Funada, 1982; Udink ten Cate and Van de Vooren, 1984; Udink ten Cate, 1985).

The validation of the control models is obtained basically by the reproducibility of the results under various conditions, which are comparable except for a single input signal. In enclosed environments like phytotrons this can be achieved by repeating the same experiment at different times. In a greenhouse, with its many uncontrollable signals due to weather, validation may be obtained by performing concurrent experiments in identical compartments (Udink ten Cate, 1983). In the physical models, validation is achieved by measuring the various sub-processes accurately in specific experiments. The best way to do this is to model and measure concurrently the climate of the same greenhouse compartment (Bot, 1983).

Another interesting aspect of the developments in control models is that development has been impeded by the attitude of researchers to the problem. Even in the last decade, the underlying philosophy has been to consider greenhouse computer controllers as *operators* manipulating various actuators. With the help of time-clocks and additional measurements the operating requirements can be transformed into procedures which are carried out by the controller/computer. In these procedures actuator settings, such as heating system temperature and ventilation window aperture, are directly related to the (assumed) effects on the crop. Such procedures may be improved by adding operator knowledge, in terms of logical decisions and conditional compensations. This type of control is the same as that found in programmable logical controllers (PLC). Low cost greenhouse computers operate in this way. However, when the construction of the greenhouse is such that the control problem is better formulated as dynamic control (in contrast to static control with a PLC) the resulting performance deteriorates quickly. One of the intriguing problems of greenhouse climate control is to find a way to combine the focus on procedures with dynamic control.

It should be mentioned that the term 'control' is generally used in a broad sense, incorporating static as well as dynamic control. In the perception of an operator, discontinuous events such as the operation of a thermal screen, or even the chalking of the glass cover of the greenhouse, are seen as control operations, and the dynamic nature of the process under control is not analysed. To emphasize the distinction: when the climate is controlled using *continuously operating* actuators, the term greenhouse climate feedback/feed-forward control (GCFFC) is introduced (Udink ten Cate, 1982, 1983).

Research on climate control reflects the operator's attitude. Relatively few studies on GCFFC have been published, but even these are restricted to the heating system control loop (O'Flaherty, Gaffney and Walsh, 1973; Tantau, 1979; Udink ten Cate and Van de Vooren, 1981; Otto *et al.*, 1982) and the air temperature inside the greenhouse (Udink ten Cate, 1983, 1985; Udink ten Cate and Van de Vooren, 1984). Experimental estimation of the GCFFC process characteristics using explicit test signals to perturb the GCFFC model was reported by Udink ten Cate (1983, 1985) and Udink ten Cate and Van de Vooren (1984). Also, Otto *et al.* (1982) and O'Flaherty, Gaffney and Walsh (1973) have suggested methods of experimental data estimation for a GCFFC model (a 'general' model as opposed to a perturbation model). Udink ten Cate (1983) has clearly demonstrated that a high-frequency perturbation model has quite different characteristics from a low-frequency model, which makes a 'general' model, combining low-frequency plus high-frequency behaviour, more complex than a GCFFC perturbation model alone.

Recently a 'general' model has been proposed, combining low-frequency and high-frequency GCFFC behaviour (Udink ten Cate, 1985). In this chapter a new 'general' GCFFC model will be proposed, incorporating the soil of the greenhouse as a heat storage element. This new model is certainly more elaborate than the perturbation-type GCFFC model, but is of low complexity when compared with a physical model, which explains why the word general is placed within inverted commas. An interesting feature of these models is that they are formulated in terms of heating-load coefficients (k -values), which makes them applicable to any greenhouse.

In addition to GCFFC modelling, attention will be paid to some algorithms which are employed in the computer control of the heating system/greenhouse air temperature control loop. Because actuator saturations have a significant impact on the control loop performance, new performance criteria are established which are typical for GCFFC. Finally, some improvements in GCFFC are suggested on the basis of the newly presented 'general' GCFFC model.

Models for GCFFC temperature control

INTRODUCTION

In the field of GCFFC most research has been devoted to the control of the air temperature inside the greenhouse, because temperature is traditionally considered to be the most important (and controllable) climate factor. In this chapter two types of models are presented: the first is a 'general' GCFFC model, incorporating soil temperature; the second is a perturbation GCFFC model, based not on the 'general' model, which is the usual mathematically oriented approach, but on a reduced greenhouse representation, which is the typical engineering approach. Being based on different assumptions, validation of the parameters of the two models leads to different values. A new approach combining the perturbation model and the 'general' model will also be presented. The perturbation model is described in detail by Udink ten Cate (1983) and the combination of the 'general' model with the perturbation model by Udink ten Cate (1985), while the 'general' model has not been published before.

4 Analysis and synthesis of greenhouse climate controllers

THE 'GENERAL' GCFFC MODEL

Figure 1.1 depicts a greenhouse and the actuators that are commonly used in GCFFC. Inside the greenhouse the air temperature θ_g ($^{\circ}\text{C}$) is regulated by heating and ventilation. The climate inside the greenhouse depends on the outside weather conditions, such as ambient air temperature θ_a ($^{\circ}\text{C}$), wind velocity v_w (m s^{-1}), wind direction, incident short-wave (solar) radiation ϕ_s (W) and long-wave radiation ϕ_l (W). Recent research in GCFFC modelling has indicated that the soil temperature also plays an important role. The soil heat storage is represented by a single layer with soil temperature θ_s ($^{\circ}\text{C}$) and at greater depth a constant soil temperature θ_{sc} ($^{\circ}\text{C}$).

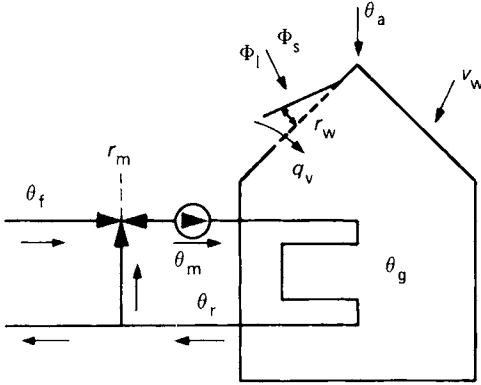


Figure 1.1 Greenhouse climate control

The greenhouse is heated by a system consisting of a heating network in which water is circulated, usually by 51 mm pipes. The inlet temperature of the pipe network is θ_m ($^{\circ}\text{C}$) and that of the outlet or return water temperature is θ_r ($^{\circ}\text{C}$), leading to an average heating system temperature of θ_h ($^{\circ}\text{C}$). The water inlet temperature is obtained by mixing return water with feedwater (from a main) of temperature θ_f ($^{\circ}\text{C}$), in a three-way mixing valve with position r_m (0–100%). Ventilation is achieved by the opening and closing of ventilation windows; the aperture is r_w (0–100%), leading to an air exchange rate of q_v ($\text{m}^3 \text{s}^{-1}$). The variable q_v is, as a rule, replaced by the ventilation rate (or air change rate) S_v (h^{-1}) which is the number of air exchanges per hour per greenhouse

$$S_v(t) \triangleq \frac{3600 q_v(t)}{V_g} \quad (1.1)$$

where V_g (m^3) is the greenhouse air volume. In an average greenhouse with single glass cladding S_v will be in the range 0.5–10 in winter conditions. In summer S_v can be up to 100.

The dynamic behaviour of the GCFFC loops can be represented in a convenient way by the introduction of incremental variables. These increments lead to a perturbation model. For example, the increment $\tilde{\theta}(t)$ of a temperature $\theta(t)$ is defined by

$$\tilde{\theta}(t) \triangleq \theta(t) - \bar{\theta} \quad (1.2)$$

The average, $\bar{\theta}$, describes the working point for the equilibrium situation which in principle is constant, but can also vary slowly in time.

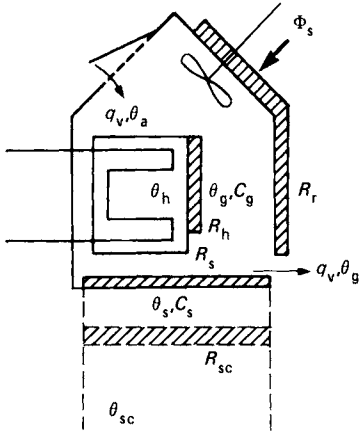


Figure 1.2 The greenhouse as a perfectly stirred tank

The ‘general’ model of the greenhouse temperature is based upon the approximation of a greenhouse as a perfectly stirred tank (*Figure 1.2*).

Considering *Figure 1.2* and assuming uniform variables leads to the following equations.

$$C_g \frac{d\theta_g}{dt} = q_v(t) c_p \rho (\theta_a(t) - \theta_g(t)) + \frac{1}{R_h} (\theta_h(t) - \theta_g(t)) + \frac{1}{R_r} (\theta_a(t) - \theta_g(t)) + \frac{1}{R_s} (\theta_s(t) - \theta_g(t)) + \eta \Phi_s(t) \quad (1.3a)$$

and

$$C_s \frac{d\theta_s}{dt} = -\frac{1}{R_s} (\theta_s(t) - \theta_g(t)) + \frac{1}{R_{sc}} (\theta_{sc} - \theta_s(t)) \quad (1.3b)$$

where C_g is the greenhouse inside heat capacity (J K^{-1}) (composed of values for air and construction parts); $c_p \approx 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$ is the specific heat of dry air at constant pressure; $\rho \approx 1.2 \text{ kg m}^{-3}$ is the air density; R_h, R_r, R_s, R_{sc} (K W^{-1}) are the thermal resistances of the heating system, the roof and sidewalls, the first layer of the soil, and the second layer of the soil, respectively; and η is the fraction of solar radiation absorbed. Note that in *Equations 1.3a,b* only convection or conduction heat fluxes are represented explicitly. Long-wave radiation heat exchange from the greenhouse roof to the sky and latent heat exchange are not taken into account. This is justified because these effects are incorporated in the way the values of the thermal resistances are obtained in practice, though this will lead to short-term errors in the GCFFC model. The fraction η indicates the conversion of solar radiation into sensible heat, and is significantly different from the greenhouse roof transmissivity.

Equations 1.3a,b are normalized in terms of units of ground area. If the ground area of the greenhouse is A_g (m^2), the normalized parameters are as follows: $C_g^* \triangleq C_g/A_g$, $C_s^* \triangleq C_s/A_g$ ($\text{J K}^{-1} \text{ m}^{-2}$); $q_v^*(t) \triangleq q_v(t)/A_g$; $k_h^* \triangleq 1/(R_h A_g)$; $k_r^* \triangleq 1/(R_r A_g)$; $k_s^* \triangleq 1/(R_s A_g)$; and $k_{sc}^* \triangleq 1/(R_{sc} A_g)$ ($\text{W m}^{-2} \text{ K}^{-1}$).

From *Equation 1.1* it follows that

$$q_v^*(t) = \frac{(V_g/A_g) S_v(t)}{3600}$$

6 Analysis and synthesis of greenhouse climate controllers

If the average height of the greenhouse is $\bar{h}_g \triangleq V_g/A_g$ it follows that

$$c_p \rho q_v^*(t) = \zeta \bar{h}_g S_v(t) \quad (1.4)$$

where $\zeta = c_p \rho / 3600 \cong 0.33 \text{ (W h m}^{-3} \text{ K}^{-1})$. Equations 1.3a,b may be re-stated as

$$C_g^* \frac{d\theta_g}{dt} = \zeta \bar{h}_g S_v(t) (\theta_a(t) - \theta_g(t)) + k_h^* (\theta_h(t) - \theta_g(t)) + k_r^* (\theta_a(t) - \theta_g(t)) + k_s^* (\theta_s(t) - \theta_g(t)) + \eta \phi_s'(t) \quad (1.5a)$$

$$C_s^* \frac{d\theta_s}{dt} = -k_s^* (\theta_s(t) - \theta_g(t)) + k_{sc}^* (\theta_{sc} - \theta_s(t)) \quad (1.5b)$$

where ϕ_s' is the radiation flux density (W m^{-2}).

Equations 1.5a,b are linear functions of θ_g , except for the first term of Equation 1.5a. Representing ventilation transfer by introducing a k -value, $k_v^* \triangleq \zeta \bar{h}_g \bar{S}_v$, and neglecting the higher-order terms, gives

$$\zeta \bar{h}_g S_v(t) (\theta_a(t) - \theta_g(t)) = k_v^* (\theta_a(t) - \theta_g(t)) + \zeta \bar{h}_g \bar{S}_v(t) (\bar{\theta}_a - \bar{\theta}_g) \quad (1.6)$$

In the following, $\bar{S}_v(t) = 0$. So far we have considered the greenhouse as a perfectly stirred tank. In reality, however, there are transport time lags in the greenhouse where the variables are represented by point measurements. Taking these into account we arrive at

$$C_g^* \frac{d\theta_g}{dt} = - (k_v^* + k_r^* + k_h^* + k_s^*) \theta_g(t) + k_h^* \theta_h(t - \tau_{d,h}) + (k_v^* + k_r^*) \theta_a(t - \tau_{d,a}) + k_s^* \theta_s(t) + \phi_s'(t - \tau_{d,s}) \quad (1.7a)$$

$$C_s^* \frac{d\theta_s}{dt} = - (k_s^* + k_{sc}^*) \theta_s(t) + k_s^* \theta_g(t) + k_{sc}^* \theta_{sc} \quad (1.7b)$$

where $\tau_{d,i}$ is the transport time lag for the particular process. Equation 1.7 forms the basis of the 'general' GCFFC model, as it is used in parameter estimation and validation. A transfer function model can be derived from Equation 1.7 and is of the type employed in control analysis. The transfer functions are of the black box type, which means that the parameters in the transfer function are composed of several parameters of the general model. In parameter estimation, usually only transfer function types of models can be validated. Therefore to interpret the resulting transfer functions in terms of physical parameters necessitates concurrent experiments in the greenhouse. The 'general' GCFFC transfer function model is depicted in Figure 1.3.

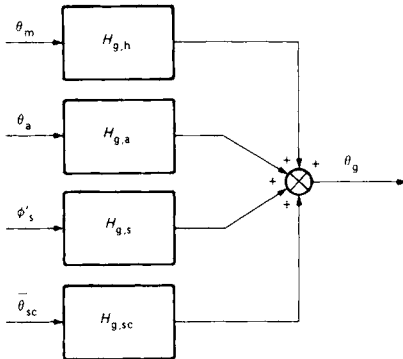


Figure 1.3 'General' GCFFC transfer function model

Taking the Laplace transform leads to the relations

$$k_{\text{tot}}^* \triangleq k_v^* + k_r^* + k_h^* + k_s^*; \quad \tau_g = C_g^*/k_{\text{tot}}^*; \quad \tau_s = C_s^*/(k_s^* + k_{\text{sc}}^*);$$

$$a = (k_{\text{tot}}^*(k_s^* + k_{\text{sc}}^*)) / (k_{\text{tot}}^*(k_s^* + k_{\text{sc}}^*) - k_s^{*2}) \quad (1.8a)$$

$$H \cong \frac{(\tau_s s + 1)}{[a\tau_g\tau_s s^2 + a(\tau_g + \tau_s)s + 1]} \quad (1.8b)$$

$$H_{g,h} \cong \frac{\theta_g(s)}{\theta_m(s)} = K_{g,h} e^{-\tau_{d,h}s} H; \quad K_{g,h} = a k_h^*/k_{\text{tot}}^* \quad (1.8c)$$

$$H_{g,a} \cong \frac{\theta_g(s)}{\theta_a(s)} = K_{g,a} e^{-\tau_{d,a}s} H; \quad K_{g,a} = a(k_r^* + k_v^*)/k_{\text{tot}}^* \quad (1.8d)$$

$$H_{g,s} \cong \frac{\theta_g(s)}{\phi_s'(s)} = K_{g,s} e^{-\tau_{d,s}s} H; \quad K_{g,s} = a\eta/k_{\text{tot}}^* \quad (1.8e)$$

$$H_{g,\text{sc}} \cong \frac{\theta_g(s)}{\theta_{\text{sc}}(s)} = K_{g,\text{sc}} H; \quad K_{g,\text{sc}} = a k_s^* k_{\text{sc}}^* / [k_{\text{tot}}^*(k_s^* + k_{\text{sc}}^*)] \quad (1.8f)$$

From *Equation 1.8* it is evident that $K_{g,h} + K_{g,a} + K_{g,\text{sc}} = 1$. Furthermore $\tau_{d,h} = \tau_{d,a}$ in most cases and $\tau_{d,s} = 1$ min, which is the sampling interval of the greenhouse computer. In the transfer function $H_{g,\text{sc}}$, the input signal for $\theta_{\text{sc}}(s)$ is either constant or varies slowly in time, so that a quasi-constant value of $K_{g,\text{sc}}$ describes the behaviour sufficiently accurately. The dead time is also not meaningful for $H_{g,\text{sc}}$ and is therefore omitted.

Experiments have been carried out in the multifactorial glasshouse of the Glasshouse Crops Research and Experiment Station at Naaldwijk, Netherlands (Udink ten Cate, 1983) in which 24 identical compartments are controlled by a computer (Van de Vooren and Koppe, 1975). Fitting of the data leads to the parameter values of *Table 1.1*. The multifactorial glasshouse consists of compartments grouped in blocks of four, with corridors between the blocks. The typical height $\bar{h}_g$ is 3 m, so that from *Equation 1.4*, $k_v^* = \bar{S}_v$. The value of k_v^* is low in the winter conditions considered here.

Table 1.1 RESULTS OF DATA FITTING FOR THE NAALDWIJK MULTIFACTORIAL GLASSHOUSE

	Night	Day
θ_{sc}	21.2 °C	22.0 °C
$C_g^*/60$	449.2	449.8
$C_s^*/60$	330.0	330.0
$k_r^* + k_v^*$	8.9	8.3
k_h^*	4.4	3.9
η	—	0.43
k_s^*	6.4	4.8
k_{sc}^*	3.0	1.1

The values of k_h^* shown in *Table 1.1* agree with the values presented by von Zabeltitz (1978). The only differences are found in k_s^* and k_{sc}^* , which lead to different characteristics in night and day situations. It is not clear yet if this is due to the structure of the glasshouse or to other physical factors. In any case, it is observed that night and day situations lead to different forms of H (*Equation 1.8b*).

8 Analysis and synthesis of greenhouse climate controllers

Typically,

$$\text{at night } H_{g,h} = 0.287 \frac{e^{-7s} (35s + 1)}{(55s + 1)(18s + 1)} \quad (1.9a)$$

$$\text{and during the day } H_{g,s} = 0.0328 \frac{e^{-s} (56s + 1)}{(83s + 1)(23s + 1)} \quad (1.9b)$$

The dead time was estimated from experiments. For both day and night conditions the sum of the dead time plus the smallest time constant was about 25 min. Also, the ratios of the other time constants of the transfer functions were similar: 0.63 in *Equation 1.9a* and 0.67 in *Equation 1.9b*. Consequently, the day and night behaviours are quite comparable, despite differences in time constants. Instead of *Equation 1.7*, transfer functions like those in *Equation 1.9* are readily employed in

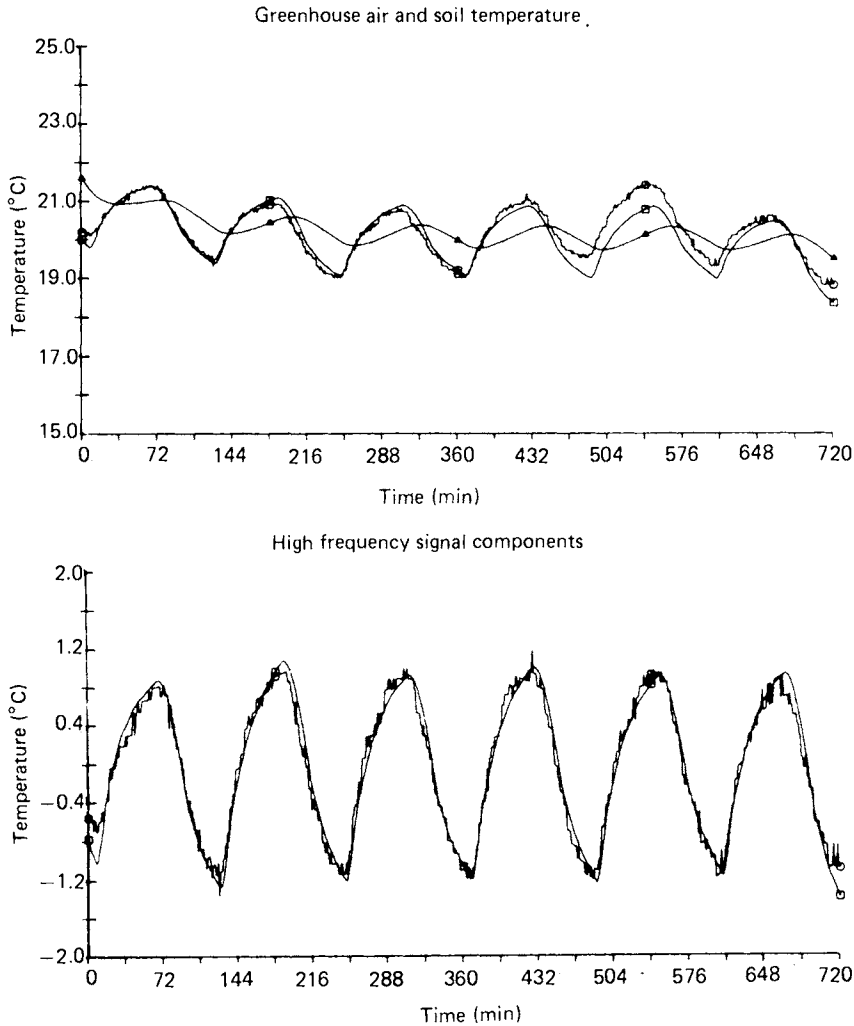


Figure 1.4 Actual (○) and simulated (□) responses of greenhouse air temperature during an experiment at night, and simulated soil temperature (▲)

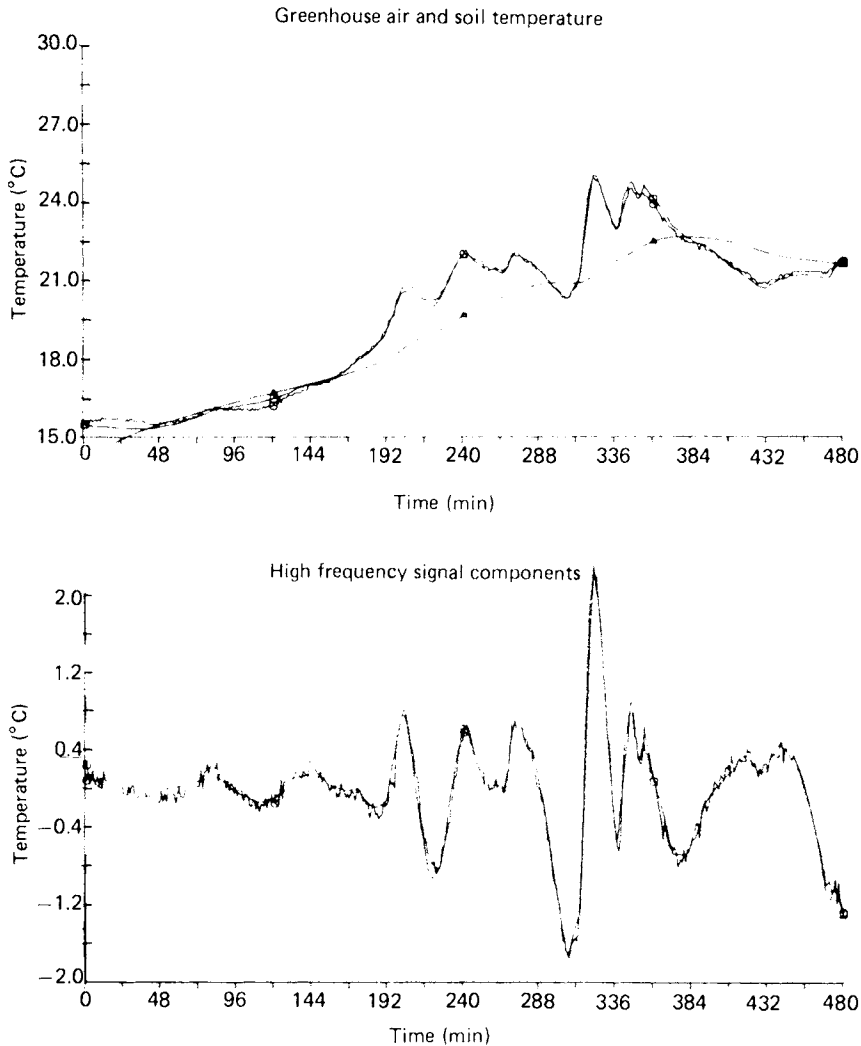


Figure 1.5 Actual (○) and simulated (□) responses of greenhouse air temperature during a day with alternating sun and cloud, and simulated soil temperature (▲)

simulation. The advantage of the transfer functions is that a better fit can be obtained than by using the physical model of *Equation 1.7*, which itself explains the form of the transfer functions.

To demonstrate the accuracy of the data fits, results are shown in *Figures 1.4* and *1.5*. *Figure 1.4* shows the results of a night experiment ($\phi_s = 0$), giving the results presented in *Table 1.1*. Both $\theta_m(t)$ and $\theta_a(t)$ are time varying, and θ_{sc} is taken as a parameter to be estimated. Also shown is the high-frequency signal component of the signals. This is done since in GCFFC the control is best tested by high-frequency perturbations. It is seen that the fit is excellent. *Figure 1.5* shows a daytime run (radiation present). Again the results are excellent (parameter values as in *Table 1.1*). The high-frequency perturbations give a good fit which, together

with *Figure 1.4*, stresses that the model presented in *Equation 1.7* and the related transfer functions of *Equation 1.8* can be employed successfully in control engineering problems.

PERTURBATION MODELS

The 'general' model is not so easily applied in GCFFC control analysis because the temperature θ_s is neither easily defined nor measured, and the k -values associated with the soil, k_s^* and k_{sc}^* , cannot be established empirically from heating load measurements as can the other k -values. Therefore, a simplified model will be presented which is valid for perturbations with respect to a working point varying slowly in time. Naturally, *Equation 1.7* can be reduced using formal methods of model order reduction. A more direct approach is to omit the soil layer characteristics from *Equation 1.3*:

$$C_{p,g} \frac{d\theta_g}{dt} = -q_v(t) c_p / \rho (\theta_g(t) - \theta_a(t)) + \frac{1}{R_{p,r}} (\theta_a(t) - \theta_g(t)) + \frac{1}{R_{p,h}} (\theta_h(t) - \theta_g(t)) + \eta_p \phi_s(t) \quad (1.10)$$

The parameters carry the subscript p to denote that they belong to the perturbation model. The values differ from those in *Equation 1.3* since the influence of the soil energy storage layer is already incorporated in their values. From *Equation 1.10* a perturbation model is derived by linearization techniques. With *Equations 1.2* and *1.6*, and after normalizing per unit greenhouse ground area,

$$C_{p,g}^* \frac{d\tilde{\theta}_g}{dt} = - (k_{p,v}^* + k_{p,r}^* + k_{p,h}^*) \tilde{\theta}_g(t) + k_{p,h}^* \tilde{\theta}_h(t) + \zeta \tilde{h}_g (\tilde{\theta}_a - \tilde{\theta}_g) \tilde{S}_v(t) + \eta_p \tilde{\phi}_s'(t) \quad (1.11)$$

Using a similar approach to *Figure 1.3*, transfer functions can be formulated. Using the Laplace transform and introducing dead times leads to:

$$k_{p,tot}^* \triangleq k_{p,v}^* + k_{p,r}^* + k_{p,h}^*; \quad (1.12a)$$

$$H_{p,h} \triangleq \frac{\tilde{\theta}_h(s)}{\tilde{\theta}_m(s)} = \frac{K_{p,h} e^{-\tau_{d,h}s}}{\tau_{p,h} s + 1}; \tau_{p,h} = C_{p,g}^* / k_{p,tot}^*; K_{p,h} = k_{p,h}^* / k_{p,tot}^* \quad (1.12b)$$

$$H_{p,v} \triangleq \frac{\tilde{\theta}_g(s)}{\tilde{S}_v(s)} = \frac{K_{p,v} e^{-\tau_{d,v}s}}{\tau_{p,v} s + 1}; \tau_{p,h} = \tau_{p,v}; K_{p,v} = \zeta \tilde{h}_g (\tilde{\theta}_a - \tilde{\theta}_g) / k_{p,tot}^* \quad (1.12c)$$

$$H_{p,s} \triangleq \frac{\tilde{\theta}_g(s)}{\tilde{\phi}_s'(s)} = \frac{K_{p,s} e^{-\tau_{d,s}s}}{\tau_{p,s} s + 1}; K_{p,s} = \eta_p / k_{p,tot}^* \quad (1.12d)$$

$$\tau_{p,s} + \tau_{d,s} = \tau_{p,h} + \tau_{d,h} \quad (1.12e)$$

Note that the time constants $\tau_{p,h}$, $\tau_{p,v}$, $\tau_{p,s}$ will not necessarily be equal, and in *Equation 1.12e* an empirical relation between them is given. The values of the parameters differ from those of *Table 1.1*; therefore *Table 1.2* presents some representative values for the Naaldwijk multifactorial glasshouse (Udink ten Cate, 1983).

Table 1.2 PERTURBATION PARAMETERS FOR NAAALDWIJK GLASSHOUSE

$k_{p,h}^* = 1.46 (\bar{\theta}_m - \bar{\theta}_g)^{0.46}$	$\eta_p = 0.7$
$k_{p,r}^* = 30$	$\tau_{d,h} = 7 \text{ min}$
$k_{p,v}^* = \bar{S}_v$	$\tau_{d,s} = 1 \text{ min}$
$C_{p,g}^*/60 = 725$ (divided by 60 in order to give $\tau_{p,}$ in min.)	

The parameters in *Table 1.2* were obtained from concurrent experiments in eight glasshouse compartments and filtering techniques were employed before the parameter estimation in order to remove the influence of disturbances. The technique is to apply a high-frequency test signal as input to one of the transfer functions, and subsequently carry out parameter estimation. This leads to estimates of the transfer function gains $K_{p,}$ and time constants $\tau_{d,}$ and $\tau_{p,}$. An additional experiment was used to estimate $k_{p,h}^*$ so that the parameters of *Table 1.2* could be calculated from *Equation 1.12*. This method is rather cumbersome and has the drawback that the accuracy of $k_{p,h}^*$ is critical. This can be checked by calculating the steady state behaviour of the simple model of *Equations 1.10* and *1.11*. The values were found to give results close to the 'physical' values presented in *Table 1.1*. It is also possible to lump the steady state characteristics and the perturbation model into a single set of transfer functions, based on *Equation 1.10* rather than on *Equation 1.3*.

COMBINED GCFFC MODELS

The combined models have a transfer function of the form of *Equation 1.8* but do not take into account the soil heat storage. This leads to results slightly different from those in *Table 1.1* since the (constant) soil temperature θ_{sc} is not taken into account. To arrive at a combined model, represented in *Figure 1.6*, the working point is described by

$$(k_{ss,h}^* + k_{ss,r}^*)\bar{\theta}_g = k_{ss,h}^*\bar{\theta}_m + k_{ss,r}^*\bar{\theta}_a + \zeta \bar{h}_g(\bar{\theta}_a - \bar{\theta}_g) \bar{S}_v + \eta_{ss}\bar{\phi}_s' \quad (1.13)$$

Here the subscript ss denotes the steady state values of the parameters. In *Equation 1.13* average values of the variables are assumed, but variables ranging slowly in time may also be employed. The 'steady state' values of the parameters for the Naaldwijk multifactorial glasshouse were found from the experiments described earlier. Using $k_{ss,h}^* = 1.0 (\bar{\theta}_m - \bar{\theta}_g)^{0.46}$ (the $k_{p,h}^*$ in *Table 1.2* is a linearized version) gives the results presented in *Table 1.3*. The results indicate that the relation for $k_{ss,h}^*$ is reasonable, although $k_{ss,r}^*$ comes out higher than k_r^* (*Table 1.1*). Using *Equation 1.13*, which describes the low-frequency signal components, and *Equation 1.12*, which describes the high-frequency behaviour, gives the combined model (Udink ten Cate, 1985):

$$k_{ss,t}^* \cong k_{ss,r}^* + k_{ss,h}^*; \quad H = \frac{(\tau_1 s + 1)}{(\tau_2 s + 1)(\tau_{c,s} s + 1)} \quad (1.14a)$$

$$H_{c,h} \cong \frac{\theta_g(s)}{\theta_m(s)} = K_{c,h} e^{-\tau_{d,h}s} H; \quad K_{c,h} = k_{ss,h}^*/k_{ss,t}^* \\ \tau_{c,h} = \tau_{p,h}; \quad \tau_1 = \tau'; \quad \tau_2/\tau_1 = K_{c,h}/K_{p,h} \quad (1.14b)$$

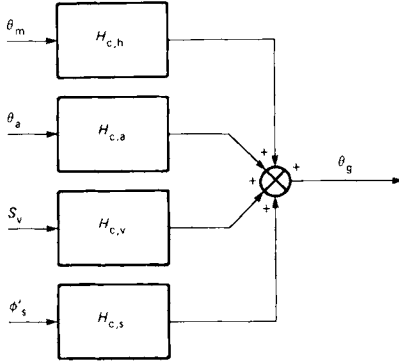


Figure 1.6 Combined GCFFC temperature transfer function model

$$H_{c,a} \triangleq \frac{\theta_g(s)}{\theta_a(s)} = K_{c,a} e^{-\tau_{d,a}s} H; K_{c,a} = k_{ss,r}^* / k_{ss,t}^* \\ \tau_{c,a} = \tau_{c,h}; \tau_{d,a} = \tau_{d,h}; \tau_2 = \tau'; \tau_2/\tau_1 = K_{c,a}/K_{p,a} \quad (1.14c)$$

$$H_{c,v} \triangleq \frac{\theta_g(s)}{S_v(s)} = K_{c,v} e^{-\tau_{d,v}s} H; K_{c,v} = \zeta h_g (\bar{\theta}_a - \bar{\theta}_g) / k_{ss,t}^* \\ \tau_{c,v} = \tau_{c,h}; \tau_{d,v} = \tau_{d,h}; \tau_1 = \tau'; \tau_2/\tau_1 = K_{c,v}/K_{p,v} \quad (1.14d)$$

$$H_{c,s} \triangleq \frac{\theta_g(s)}{\phi'_s(s)} = K_{c,s} e^{-\tau_{d,s}s} H; K_{c,s} = \eta_{ss} / k_{ss,t}^* \\ \tau_{c,s} + \tau_{d,s} = \tau_{c,h} + \tau_{d,h}; \tau_1 = \tau'; \tau_2/\tau_1 = K_{c,s}/K_{p,s} \quad (1.14e)$$

The choice of τ' is in principle arbitrary ($\tau' \approx 2$ to 3 times $\tau_{p,h}$). Note that $K_{c,h} + K_{c,a} = 1$. Because of the definition of $K_{c,v}$, the approximation in Equation 1.14 is only valid for small $\bar{S}_v$. Figure 1.7 shows results (comparable to Figure 1.4) for a night run. The responses were similar to those in Figure 1.4 and daytime results were similar to those in Figure 1.5.

Table 1.3 STEADY STATE PARAMETERS (UDINK TEN CATE, 1983)

Experiment	$k_{ss,r}^*$	$k_{p,r}^*$	$k_{p,r}^* / k_{ss,r}^*$	η_{ss}	η_p	η_p / η_{ss}
Night	9.9	29.7	3.0	—	—	—
Day	7.7	21.8	2.8	0.45	0.7	1.6

ACTUATORS

The GCFFC models considered so far have not been formulated in terms of the actuator positions r_m and r_w . This is partly because of the non-linearities introduced by the actuators. Another reason is that the actuator characteristics are quite different for various makes, and as a result lack generality. For a control system, however, the actuator operations are the inputs of the climate response. Some tentative results will therefore be presented here. For the standard mixing valve the response of temperature $\theta_m(t)$ to valve position r_m , in %, is given by

$$\theta_m(t) = [(1 - r_m(t))0.01]\theta_f(t) + r_m(t) 0.01 \theta_i(t) \quad (1.15)$$

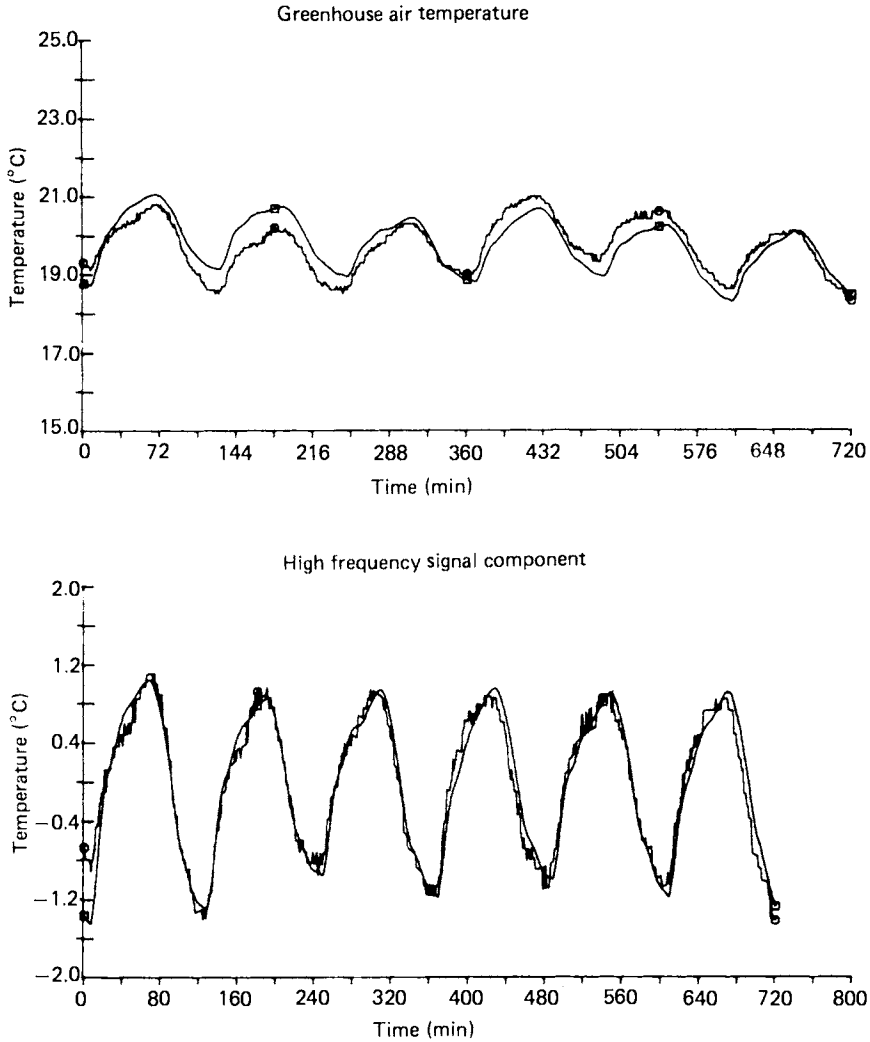


Figure 1.7 Comparison of measured (○) and simulated (□) responses (see also Figure 1.4)

Since $\theta_m(t)$ is usually controlled by an inner (slave) control loop, Equation 1.15 is accurate enough. The value of $\theta_r(t)$ depends on type and surface of the heating pipe network and on the residence time of the water in the pipes. Udink ten Cate (1983) and Van Rhijn (1984) give the relation

$$\theta_r(s) = \frac{e^{-\tau_{d,m}s}}{\tau_m s + 1} [\theta_m(s) - K_m(\theta_m(s) - \theta_g(s))] \quad (1.16)$$

with τ_m typically 2 min, and $\tau_{d,m}$ depending on the flow rate of the water in the heating pipes (in the Naaldwijk glasshouse 6 min). K_m depends on the water temperature decrease; in the Naaldwijk glasshouse the heating pipe network heating capacity C_h^* is $16.24 \text{ kJ K}^{-1} \text{ m}^{-2}$. With $\tau_{d,m} = 6 \text{ min}$, this gives $K_m = 0.089$, with $k_h^* = 4.0$.

14 Analysis and synthesis of greenhouse climate controllers

Bot (1983) and Nederhoff, Van de Vooren and Udink ten Cate (1985) have established an empirical relation for the Naaldwijk multifactorial glasshouse between ventilator position (r_w) and ventilation rate, as

$$\bar{S}_v = (1.0 + \bar{r}_w) 0.064 \bar{v}_w \quad (1.17)$$

This relation is valid for lee-side ventilation, $r_w = 0\text{--}30\%$ and v_w in the range $1\text{--}10 \text{ m s}^{-1}$. Equation 1.17 can also be linearized for perturbations, although no experimental data are available in this case.

Thus, the GCFFC models presented in this chapter facilitate analysis of GCFFC control loops (notably using the perturbation models), as well as synthesis by simulation using either the 'general' model or the combined model. The combined model may also be used when no data on the greenhouse soil temperature are to hand.

Control of the greenhouse temperature

TYPICAL PERFORMANCE CHARACTERISTICS

In GCFFC the control of the inside air temperature has received most attention in the literature. Temperature control is achieved by heating and/or by ventilation. In some cases heating and ventilation may occur together in order to lower the relative humidity, but always at low ventilation rates because of the cost of ventilation in heat loss. Carbon dioxide is also supplied via ventilation.

In temperature control, the temperature is changed according to blue prints, which are crop-specific and change with season. During the night the set (minimum) temperature is lower than during the day, and radiation is used as a heat source as much as possible, since solar radiation is free of charge. Ventilation occurs when the temperature is too high, usually determined by the acceptable environment for labour.

A complication in GCFFC is that the heating system temperature can increase only via the actuator (the mixing valve) and decrease only via heat transfer into the greenhouse. Essentially, the heating system is non-linearly saturated and as a result is asymmetrical. This asymmetry causes a typical behaviour which is different from a normal, linear, control system. Therefore, additional performance criteria must be formulated, which are typical for GCFFC (and other heating systems with a heating pipe network).

Consider Figure 1.8 where a representative response of GCFFC control is presented for a bright winter day with relatively strong radiation during the day and a cold night. Here, u_g is the desired value of θ_g . In the morning the set point u_g rises and subsequently θ_m rises. Because the increase of θ_m is relatively slow, because not only the greenhouse but also the whole greenhouse complex has to be heated, a large error ($u_g - \theta_g$) accumulates in time. In most controllers this gives rise to strong actuator signals, resulting in an 'overshoot'. This overshoot is partly caused by free solar radiation but also partly by the heat in the heating system, which is a waste. In the afternoon the radiation decreases causing a 'sag', the effect of which is hidden by a sharp decrease of u_g . At the end of the afternoon, when u_g is put on its low night value, an 'undershoot' occurs which may persist for several hours. This undershoot is the most detrimental of the undesired effects, because in winter the desired night temperature is the minimum acceptable value below which the

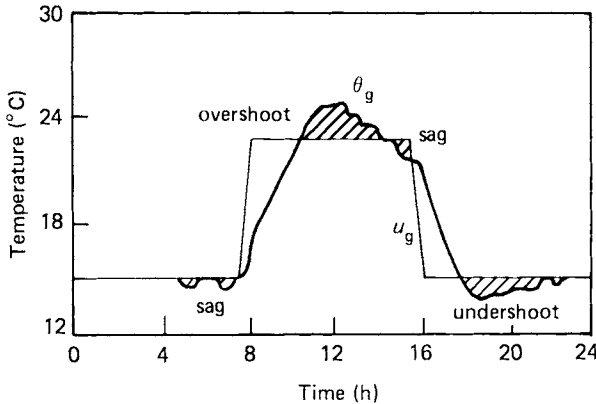


Figure 1.8 Typical GCFFC performance

temperature should not drop. Note that the steady state at night is controlled satisfactorily, although just before dawn sag again occurs.

The above description leads to a way to characterize the GCFFC behaviour in terms of: (1) undershoot (which is very much unwanted); (2) sag; and (3) overshoot (which is not wanted when it is caused by the heating system). Udink ten Cate (1983) gave a detailed description of various control algorithms which have been evaluated in practice. These algorithms will not be considered here but a brief outline of a typical algorithm will be presented in the following section, based on the GCFFC models above.

HEATING SYSTEM CONTROL SCHEME

The commonly employed control scheme for greenhouse temperature is shown in *Figure 1.9*. Here a cascade or master–slave configuration is shown. The slave loop controls the heating pipe temperature θ_m . The master regulates the slave by imposing a desired value of θ_m on the slave input, denoted as u_m . The algorithms shown in *Figure 1.9* are realised in a greenhouse climate computer.

The activation of the slave loop is initiated by changes in the temperature of the return water, θ_r , and the feedwater, θ_f . The dynamic behaviour of the slave is fast compared to that of the master. For increasing u_m or small, decreasing values of u_m the slave behaves linearly and can be regarded as transparent. When u_m decreases

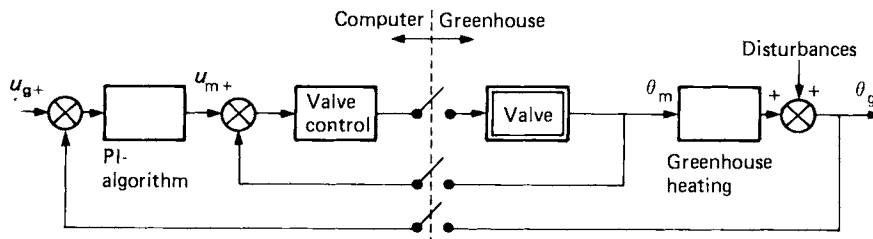


Figure 1.9 Master–slave control of greenhouse air temperature

16 Analysis and synthesis of greenhouse climate controllers

more than a few tenths of a degree per sampling interval, the mixing valve will close completely ($r_m = 0$) and in dynamic terminology a 'constraint' or saturation occurs.

The master controller is of the PI (proportional plus integral) type, where the transfer function is

$$H_r(s) = K_r \left(1 + \frac{1}{\tau_i s} \right) \quad (1.18)$$

The parameters of the controller are selected using the perturbation model $H_{p,h}$. The 'general' transfer function $H_{g,h}$ is not employed, since its precise form is seldom known in practice (although in this case we could employ $H_{g,h}$ because its form is known). The slave loop is considered to be transparent, which means that the design is only valid for upward changes of u_g and for steady state control (at night); for larger downward steps *see* Udink ten Cate (1983).

For the Naaldwijk glasshouse the transfer function becomes

$$H_{p,h} = \frac{0.25e^{-8s}}{20s + 1} \quad (1.19)$$

using worst case values for $K_{p,g}$ and $\tau_{p,h}$. The dead time includes the delay introduced by the actuator circuit of the digital controller: $\frac{1}{2}T_s$, where $T_s = 1$ min is the typical GCFPC sampling period. The sampling period is sufficiently small to allow a continuous time analysis. Using Bode plots it is readily seen that $\tau_i = 30$ min and $K_r = 10$ would satisfy stability criteria. In passing, it is worth mentioning that this quasi-continuous approach to discrete time control will not necessarily give good results. Sometimes it is better to reduce the sampling rate (longer T_s) in order to improve the control, for example in cases which have a zero mean but exhibit large fluctuations about the mean, as with ventilation control.

The PI algorithm is formulated in discrete time as follows

$$u'(k) = k_p e(k) \quad (1.20a)$$

$$u''(k) = k_i \sum_{j=0}^{k-1} e(k-j) = u''(k-1) + k_i e(k) \quad (1.20b)$$

$$u(k) = u'(k) + u''(k) \quad (1.20c)$$

Here, $u(k) = u(t)$ at time $t = kT_s$, where T_s is the sampling period. The error $e(k)$ is the controlled variable $\theta_g(k) - u_g(k)$. The numbers k and j are integers, and k_p and k_i are gain factors. The signal $u(k) = u_m(k)$ of the master controller. Equation 1.20a gives the proportional action and Equation 1.20b the integral action. Compared to the continuous time $H_r(s)$,

$$k_i = K_r T_s / \tau_i; k_p = K_r \quad (1.20d)$$

In the discrete PI controller the value of $u(k)$ is clamped between a minimum and a maximum value $L_{\min} \leq u(k) \leq L_{\max}$. This prevents damage to the crop by burning at high θ_m and prevents diseases at low θ_m . Also, the clamping of the signal $u(k)$ is essential in discrete control: when the error $e(k)$ cannot be made zero because of saturation in the control loop, the value of $u(k)$ goes to infinity because $u''(k)$ accumulates. In an electronic controller $u(k)$ is limited automatically by the value of the supply voltage, but in a computer algorithm explicit limits must be imposed. An anti-wind-up procedure is therefore incorporated in the program with an imposed $L_{\min}$ and $L_{\max}$.

The control of the slave loop is proportional according to $u'(k)$ in *Equation 1.20a*. Here $e(k) = u_m(k) - \theta_m(k)$. For the example at hand, $k_p = 2.5$ is selected. The controller output is a time-proportional signal which steers the mixing valve motor 2.5 s for each °C error, by closing a relay at the beginning of every sampling interval. The maximum time of opening is 15 s, the minimum (threshold) is 1 s. This type of time-proportional control is quite common in low-cost computer control, where it is not required that an instantaneous change is made at every $t = kT_s$. In our case the actuation time is small as compared with T_s , so that no problems will arise ($T_s = 1$ min).

In the master-slave configuration the master controller regulates the slave controller. The master therefore controls the value of $\theta_g(k)$ via minimization of $e(k)$. This type of controller performs position control. The slave controller controls $\theta_m(k)$ via the actuation of the mixing valve motor. The slave output regulates the changes of the motor position and is therefore called a 'velocity controller'. The mixing valve motor performs a pure integrative action. This explains why the additional $u''(k)$ term is not applied in the slave, since this would lead to instability.

Ventilation control is similar to temperature control (for a detailed description see Udink ten Cate, 1983). However, in order to avoid concurrent heating and ventilation, the set point of the ventilation master controller is set 1 to 2 °C above that of the heating system. Another pertinent problem is that the window motor must not be operated too often in order to avoid wear and tear of the window mechanism. In practice a variety of methods is employed to reduce the number of actuator operations.

NEW CONTROL ALGORITHMS

With the GCFFC models new methods can be found in order to improve the controller performance. An obvious method is feed-forward compensation. When the effects of disturbances are known, the dynamic influences can be compensated for. An example is for changes in radiation. From the 'general' GCFFC model (*Equation 1.8*), as well as from the combined model (*Equation 1.14*), it is seen that the transfer functions $H_{g,h}$ and $H_{g,s}$ or $H_{c,h}$ and $H_{c,s}$ are comparable dynamically (because the difference in time constants matches the difference in dead times, see *Equation 1.14e*). In *Figure 1.10* a feed-forward configuration is presented. With

$$H_x(s) = \eta/k_h^* \quad (1.21)$$

exact compensation is obtained. It is interesting to note that the transfer functions will be similar for any greenhouse, so that *Equation 1.21* has a broad range of validity. Similar feed-forward compensation can be applied for other external influences.

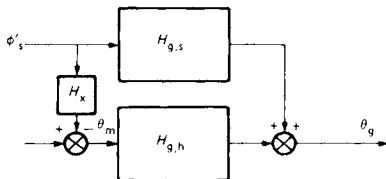


Figure 1.10 Feed-forward compensation

Another way to use the models presented in this chapter is to calculate the relevant parameters on-line. Tantau (1985) uses the simple model of *Equation 1.13* in order to calculate a heat balance. With some additional assumptions, a fairly accurate estimation can be made of the required θ_m for a given θ_g , depending on external influences. This calculation could be carried out at night and used to predict the response of θ_g to assumed solar radiation. Although the $k_{ss,}$ values are not equal to the heating load coefficients k^* , a very much improved performance is possible.

The aforementioned examples indicate that using the knowledge of the greenhouse dynamic behaviour will allow many new control methods to emerge. This will lead to interesting developments, especially in predictive algorithms.

Conclusions

In this chapter the emphasis has been placed on the development of GCFFC models for temperature control. These models are seen to correspond closely to measured data. Because the models are formulated in terms of heating load coefficients, which are widely available in the literature, they are readily formulated for an arbitrary greenhouse. Several types of GCFFC models are presented. A 'general' GCFFC model, which also describes the greenhouse soil temperature, is used as a starting point. Subsequently, a perturbation model is formulated from a model not incorporating the soil. This perturbation model has only limited validity but can be employed for control analysis—especially the linear behaviour of the control loop. A combination with the simple model (for perturbations) and the transfer functions of the type that can be derived from the 'general' model is also presented. This gives us a family of GCFFC models that have wide applications in the greenhouse climate control field. It is my belief that a completely new area of GCFFC control can be developed from the models presented.

References

- BOT, G.P.A. (1983). 'Heat transfer and ventilation in glasshouses'. Dissertation, Agricultural University, Wageningen, Netherlands
- BUSINGER, J.A. (1963). The glasshouse (greenhouse) climate. In *Physics of Plant Environment*. pp. 277–318. Ed. by van Wijk, W.R. North-Holland, Amsterdam
- GARZOLI, K.V. and BLACKWELL, J. (1973). The response of a glasshouse to high solar radiation and ambient temperature. *Journal of Agricultural Engineering Research*, **18**, 205–216
- HASHIMOTO, Y., MORIMOTO, T. and FUNADA, S. (1982). Identification of water deficiency and photosynthesis in short term plant growth under random variation of the environment. In *Preprints, 6th IFAC Symposium, Identification and System Parameter Estimation*, vol. 2. Arlington, Virginia, USA. Pergamon, Oxford
- KIMBALL, B.A. (1973). Simulation of the energy balance of a greenhouse. *Agricultural Meteorology*, **11**, 243–260
- NEDERHOFF, E.M., VAN DE VOOREN, J. and UDINK TEN CATE, A.J. (1985). A practical tracer gas method to determine ventilation in greenhouses. *Journal of Agricultural Engineering Research*, **39**, 309–319

- O'FLAHERTY, T., GAFFNEY, B.J. and WALSH, J.A. (1973). Analysis of the temperature control characteristics of heated glasshouses using an analogue computer. *Journal of Agricultural Engineering Research*, **18**, 117–132
- OTTO, P., SOKOLLIK, K., WERNSTEDT, J. and DIEZEMANN, M. (1982). Ein Innentemperaturmodell zur Mikrorechnersteuerung der Heizungssysteme von Gewächshäusern. *Archiv für Gartenbau*, **30**, 139–146 (In German with English summary)
- TAKAKURA, T., JORDAN, K.A. and BOYD, L.L. (1971). Dynamic simulation of plant growth and environment in the greenhouse. *Transactions of the American Society of Agricultural Engineers*, **14**, 964–971
- TANTAU, H.J. (1979). *Analyse des Regelverhaltens klimatisierter Gewächshäuser als Grundlage zur Auswahl und Entwicklung geeigneter Regler*. Gartenbautechnische Informationen Heft 7. Taspo Verlag, Hannover, Federal Republic of Germany (In German)
- TANTAU, H.J. (1985). Greenhouse climate control. *Acta Horticulturae*, **174**, 449–459
- UDINK TEN CATE, A.J. (1982). What is the problem in greenhouse climate control? *Proceedings International Techn. Kolloquium*, Heft 2, Techn. Univ. Ilmenau, DDR. pp. 207–210.
- UDINK TEN CATE, A.J. (1983). 'Modeling and (adaptive) control of greenhouse climates.' Dissertation, Agricultural University, Wageningen, Netherlands
- UDINK TEN CATE, A.J. (1985). Simulation models for greenhouse climate control. In *Proceedings, 7th IFAC Symposium. Identification and System Parameter Estimation*, York, England. Pergamon, Oxford
- UDINK TEN CATE, A.J. and VAN DE VOOREN, J. (1981). Adaptive systems in greenhouse climate control. In *Proceedings, 8th IFAC World Congress*, Kyoto, Japan. Late papers, pp. 9–15. Pergamon, Oxford
- UDINK TEN CATE, A.J. and VAN DE VOOREN, J. (1984). Modelling of greenhouse climates using time-series analysis techniques. In *Proceedings, 9th IFAC World Congress*, Budapest, Hungary. Vol. I, pp. 272–279. Pergamon, Oxford
- VAN BAVEL, C.H.M., DAMAGNEZ, J. and SADLER, E.J. (1981). The fluid-roof solar greenhouse: energy budget analysis by simulation. *Agricultural Meteorology*, **23**, 61–76
- VAN RHIJN, C.H. (1984). ['Modelling of a greenhouse heating system.'] M.Sc. thesis, Agricultural University, Wageningen, Netherlands (In Dutch)
- VAN DE VOOREN, J. and KOPPE, R. (1975). The climate glasshouse at Naaldwijk. *Netherlands Journal of Agricultural Science*, **23**, 238–247
- ZABELTITZ, C. VON (1978). *Gewächshäuser—Planung und Bau*. Verlag Eugen Ulmer, Stuttgart, Federal Republic of Germany (In German)

THE MODELLING AND CONTROL OF NUTRIENT FILM SYSTEMS

PETER YOUNG, M.A. BEHZADI and ARUN CHOTAI

University of Lancaster, UK

and

PAUL DAVIS

National Institute of Agricultural Engineering, UK

Introduction

Until comparatively recently, glasshouse crops were grown conventionally in a soil medium. However, the energy crisis of the 1970s introduced certain economic difficulties: the greenhouse soil had to be heated during winter, and it required steam sterilization between the removal of an old crop and the planting of a new one. Other disadvantages of cultivation in soil arose from factors such as poor soil structure, variable water content and the accumulation of soluble salts. As a result, commercial growers now find that it can be more economical to grow the plants in other ways, such as in containers of peat or other substrates.

Another way to cultivate glasshouse plants is by the nutrient film technique (NFT), originally developed as a research tool at the Glasshouse Crops Research Institute (GCRI), in order to monitor the growth of tomato plant roots in water culture (Cooper, 1967). The potential commercial advantages of this system were soon recognized and it was quickly adopted by a number of growers during the 1970s. It is still used at GCRI as a research tool; for instance, plant transpiration rates can be measured quite straightforwardly in such an NFT system (Winsor, Hurd and Price, 1979).

In the NFT, a shallow stream of nutrient solution is circulated over the bare roots of the growing plants in order to provide adequate water, nutrients and aeration. The temperature, nutrient concentration and acidity of the solution are all monitored and controlled. An extensive exposition of the method is given in a paper by Graves (1983). The seeds are sown in small containers, usually containing a 'rockwool' substrate; when the seedlings are large enough the containers are placed in slightly sloping gulleys or channels formed of plastic sheeting. Nutrient solution trickles down the channels into a catchment trench and is then recirculated. The roots of the plants soon grow out of the bottom ends of the containers and into the channels.

Figure 2.1 is a diagram of the experimental system used at the National Institute of Agricultural Engineering (NIAE). The arrows indicate the direction of flow along the channels and pipework. In addition to the return pipe from the catchment trench, there is also a sampling line to a conductivity and pH controller; this line returns sampled nutrient to the trench, together with any added salts or acid.

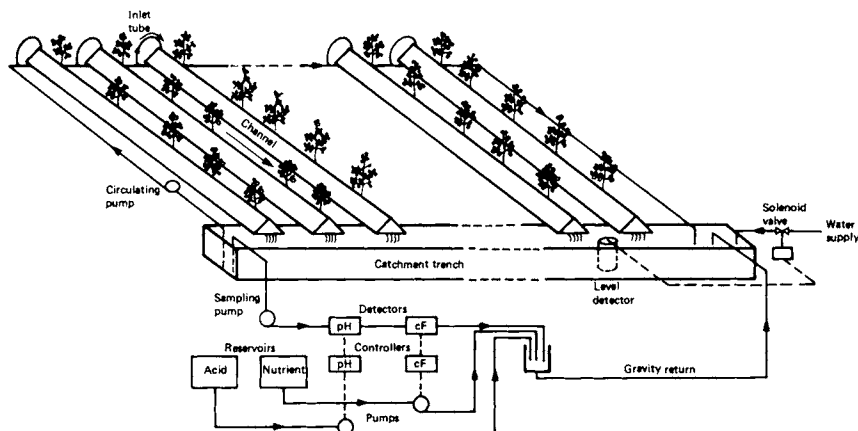


Figure 2.1 The NIAE experimental nutrient film system

NFT culture is very suitable for tomato plants and they are being grown in the experimental system at NIAE. However, the technique is not successful with all crops; for example, it is thought that extensive die-back often suffered by the roots of cucumbers in NFT culture results from the strong inhibition to the flow of nutrients caused by their large root mass (Starky, 1979).

Tomato plants can tolerate quite a wide range of nutrient concentrations but fruit quality suffers at low concentrations (Winsor and Massey, 1978). Consequently, it is necessary to maintain good (but not tight) control of the ion concentrations in the solution. In the early days of NFT, nutritional problems were not uncommon: it was not always appreciated that, in contrast to the liquid feeding of plants in greenhouse soils or peat bags, an NFT system requires the addition of up to 12 nutrients, although most of these need only be present in small quantities. Until recently, only the conductivity and pH of the nutrient solution could be monitored frequently, and the balance of different ions in solution had to be checked at 1- to 3-week intervals by chemical analysis. However, equipment has now been developed at Imperial College* for the measurement of some of the most important nutrient ion concentrations, namely potassium, nitrate and calcium. The equipment can also measure pH and the concentrations of the unwanted sodium and chloride ions which accumulate in the system. The equipment is being tested at NIAE and at GCRI and it is anticipated that its use in a suitable control system will permit better control of the ion concentrations and a less frequent need for chemical analysis.

Up to the present, simple on/off control has been applied for the addition of salts and acid to the nutrient solution, in order to try to maintain the conductivity and pH between acceptable set levels. Nutrient or acid is pumped into the system when either conductivity or pH, respectively, reaches the set level; the pump is switched off again when it reaches another set level. With the prospect of more detailed monitoring of ion concentrations, however, the possibility of using more sophisticated forms of control is being studied by the Environmental Control and

*This ion selective electrode system has been developed by R. Svenberg and B. Haggett, under the direction of Professor Aubrey in the Department of Chemistry.

Systems Group in the Department of Environmental Science at the University of Lancaster, in collaboration with the NIAE. So far, these studies have involved the investigation and modelling of the nutrient delivery system in the NFT process at NIAE. The primary objective of the project is the design and implementation of a direct digital control (DDC) system which may make use of the new measurement techniques but which is simple enough to use in commercial systems.

This chapter describes the experimental investigations and modelling studies conducted in the first year of this joint Lancaster/NIAE project. It also presents initial thoughts on the kind of DDC system design that seems most appropriate to the NFT system. This includes the evaluation by computer simulation of a simple self-adaptive control (SAC) system and a more comprehensive simulation study of a fixed-gain controller which fully exploits the discrete-time nature of DDC (rather than the more conventional approach of attempting to mimic an analogue controller using digital methods). This system, which works on a coarse sampling interval of 2 h and is designed using sampled-data state-variable feedback pole assignment methods, yields a controlled system which seems resilient to quite large changes in both the nutrient uptake rate by the plants and the flow characteristics of the nutrient delivery system.

A control model for the NFT system

Design methods for systematic control systems depend for their success on the availability of a suitable dynamic model of the process to be controlled. In the case of the NFT system, little research had been carried out on the overall dynamics of the system prior to the start of the project, and it proved necessary to plan a series

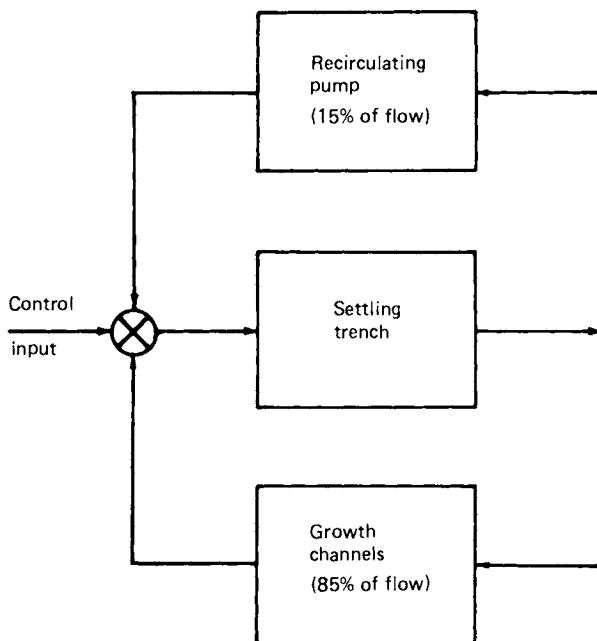


Figure 2.2 Simplified block diagram of the NIAE nutrient film system

of experiments aimed at evaluating the major dynamic elements within the system. As we can see from *Figure 2.1* and the simplified block diagram shown in *Figure 2.2*, the NFT process is dominated, in this dynamic sense, by the nutrient delivery system, in which the nutrient mixture is recirculated continually through the parallel growth channels and the catchment trench. It is clear, therefore, that a model of this nutrient delivery system is an essential part of any mathematical representation of the NFT system.

Before considering the modelling of the nutrient delivery system, however, it should be emphasized that we are not concerned here with a comprehensive simulation model, of the type that might be useful in process design or operator training applications. Rather, we will consider a 'control model'—a model which represents the dynamic behaviour of the system only to a degree which is necessary for control system synthesis. Unlike the more complex simulation model, which contains elements representing most of the physical components of the complete system, the control model is intended to characterize only the 'dominant modes' of dynamic behaviour (e.g. Young, 1978). The manner in which we characterize this dominant mode behaviour is influenced, to some extent, by the nature of the control system itself, as we shall see *below*.

THE DYNAMIC BEHAVIOUR OF THE GROWTH CHANNELS

When the nutrients are added to the catchment trench, it takes some time for them to become uniformly dispersed throughout the system and the control action which governs their addition should take these transient dynamics into account. In the NIAE system, the flow along the channels is impeded by the roots of the tomato plants and, when the plants are fully grown, most of the nutrient solution resides in the channels. Consequently, the concentration of the nutrient ions in the catchment trench is not necessarily a reliable measure of its average concentration in the system unless the ions have had an adequate time to disperse throughout the system as a whole.

It was evident from the start of the project that the flow characteristics of the channels change quite radically as the plants grow. However, since so little was known about this aspect of the NFT system, the dynamic behaviour was investigated by means of a series of tracer studies carried out at three different stages in the growth of the tomato plants. These experiments were timed at 4, 17 and 28 weeks after sowing and involved the injection of a concentrated potassium nitrate solution as a suitable tracer material.

The tracer was introduced as an impulse dose at the head of the channels and its concentration was inferred from conductivity measurements at various locations down the channel, using specially developed electrodes constructed from pencils. These electrodes proved necessary because of the extreme shallowness of the nutrient solution in the deformable plastic sheeting channels. The conductivity was monitored at a uniform sampling rate of 10 s by a data logging system based around an EPSON HX-20 microcomputer with an integral 8-channel, analogue-digital conversion system developed in the Department of Environmental Science at Lancaster. This data logging system is actually part of a more sophisticated, 'intelligent' data acquisition system that has been developed separately for a NERC-sponsored research programme on the dispersion of pollutants in rivers.

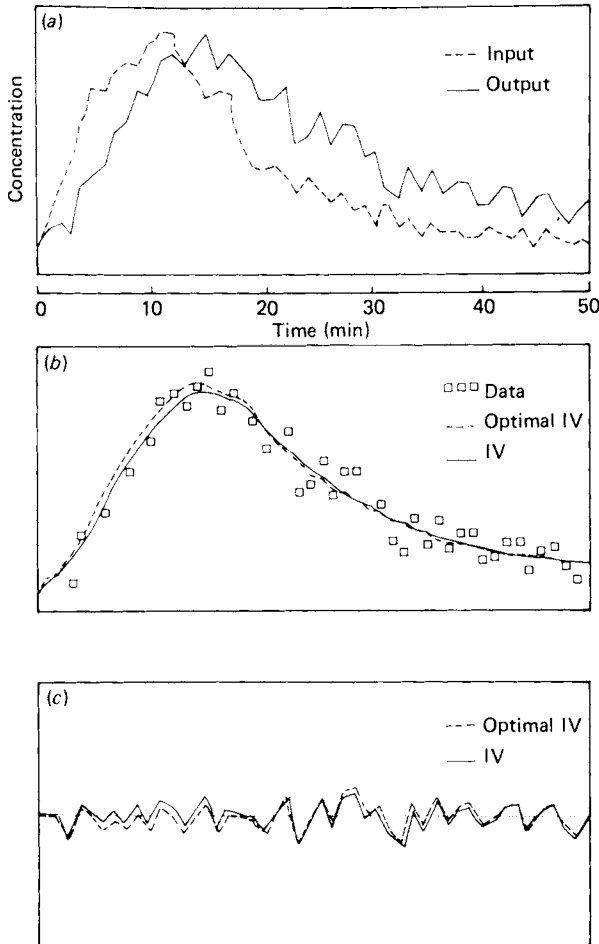


Figure 2.3 Estimation results for a 4m length of channel exhibiting a long transportation time delay (570s): (a) input–output data; (b) instrumental variable (IV) and refined (optimal) IV estimated model outputs compared with the measured output; (c) model fitting error. The data sampling interval is 60s and the input–output data are shifted in time to remove the transportation time delay τ

A typical set of experimental data, obtained after 28 weeks of plant growth from two adjacent sampling locations spaced 4 m apart in one of the channels, is shown in *Figure 2.3(a)*. There are a number of ways in which these data could be modelled but previous experience with channel dispersion models at Lancaster suggests that the most appropriate model, certainly from an operational control standpoint, is the aggregated dead-zone (ADZ) model of Beer and Young (1983). This model was developed originally for the modelling of pollutant transportation and dispersion in rivers but it appears to have much wider application potential, in areas such as the characterization of macropore effects in soil–water studies and translocation behaviour in plants (Young, 1985). It seems particularly well suited to the NFT channel system, where the growth of the plant roots can be assumed to

introduce mixing cells or 'dead-zones' which differentially delay the transport of the dissolved substances.

The ADZ model can be developed most simply by considering the mass balance of the nutrient over a length of channel, considered as a continuous stirred tank (CSTR). This produces a differential equation of the following general form

$$\frac{dx(t)}{dt} = -(r + \frac{1}{T}) x(t) + \frac{1}{T} u(t - \tau) \quad (2.1)$$

where $u(t)$ is the input (upstream) nutrient concentration ($\text{mg } \ell^{-1}$) at time $t(\text{s})$; $x(t)$ is the output (downstream) concentration ($\text{mg } \ell^{-1}$); T is the ADZ residence time (s), defined as V_E/Q where Q is the flow rate and V_E is the ADZ volume; τ is the transportation time delay, i.e. the time between the first arrival of nutrient at the upstream measurement location and its subsequent first arrival at the downstream location; and r is the 'decay-rate' (s^{-1}) associated with the loss of nutrient which, in this case, is a function of nutrient uptake rate of the plants. The 'steady state gain', G , for this system, which is obtained by setting $dx(t)/dt = 0$ and solving for the resulting equilibrium relation between x and u , is given by

$$G = \frac{1}{1 + rT} \quad (2.2)$$

For no nutrient losses ($r = 0$), therefore, the steady state gain is seen to be unity, indicating a 'conservative' system.

If Equation 2.1 is considered in discrete-time, sampled-data terms, with a sampling interval Δt s, then the relation between the downstream concentration at the k th sampling interval, x_k , and the upstream concentration, $u_{k-\delta}$, measured δ sampling intervals previously, is given by

$$x_k = -a_1 x_{k-1} + b_0 u_{k-\delta} \quad (2.3)$$

Here, δ is the pure time delay, τ , measured in sampling intervals, and is the nearest integer value of $\tau/\Delta t$.

In Equation 2.3 the model parameters a_1 and b_0 can be related to T and G by the following expressions (see e.g. Young, 1984)

$$a_1 = -\exp(-\frac{(1 + rT)\Delta t}{T}); b_0 = G(1 + a_1) \quad (2.4)$$

Strictly, these relations are exact only if the input u_k is constant over the sampling interval Δt , and $\tau/\Delta t$ is a pure integer value; however, they provide a quick and easy evaluation of the discrete-time model in the more physically meaningful continuous-time terms of Equation 2.1.

The representation Equation 2.3 is a first-order example of a general class of time-series models that have received considerable attention in the systems and statistical literature over the past 20 years (see e.g. Chatfield, 1984; Young, 1984). By the introduction of the backward shift operator z^{-1} , i.e. $z^{-1}x_k = x_{k-1}$, the equation can be converted into the following 'transfer function' (TF) form

$$x_k = \frac{b_0 z^{-\delta}}{1 + a_1 z^{-1}} u_k \quad (2.5)$$

The serial connection of a 'suitable' number of such transfer functions, as shown in Figure 2.4, provides the required model for a complete single channel system.

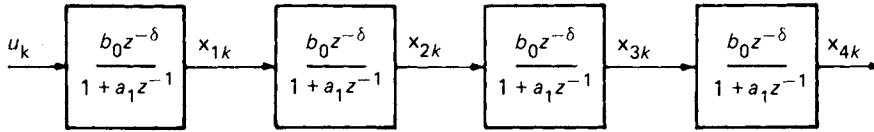


Figure 2.4 Block diagram of transfer function model for a complete channel, represented as a serial connection of aggregated dead-zone elements

The model parameters a_1 , b_0 , and δ , as well as the appropriate number of ADZ elements required to characterize any length of channel, are estimated using the recursive instrumental variable (IV) method of time-series analysis (Young, 1984, 1985) available in the microCAPTAIN microcomputer program package developed at Lancaster.

Typical results from such estimation analysis are presented in *Figures 2.3* and *2.5* where it will be seen that, despite the evident measurement noise on the input–output signals in *Figures 2.3(a)* and *2.5(a)*, the estimation procedure produces good model fits to the data. In the case of *Figure 2.3*, for example, the

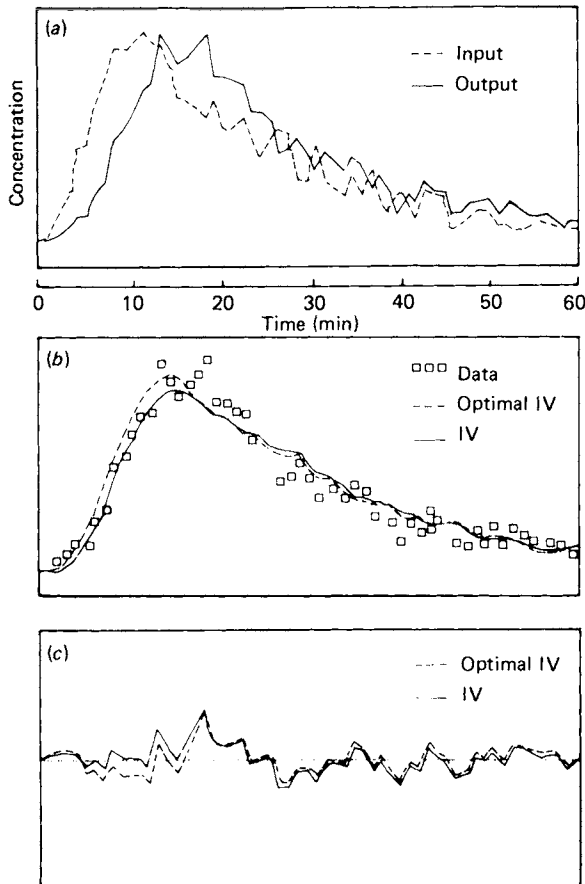


Figure 2.5 Estimation results for a 4m length of channel with a medium transportation time delay (360s). Other information as for *Figure 2.3*

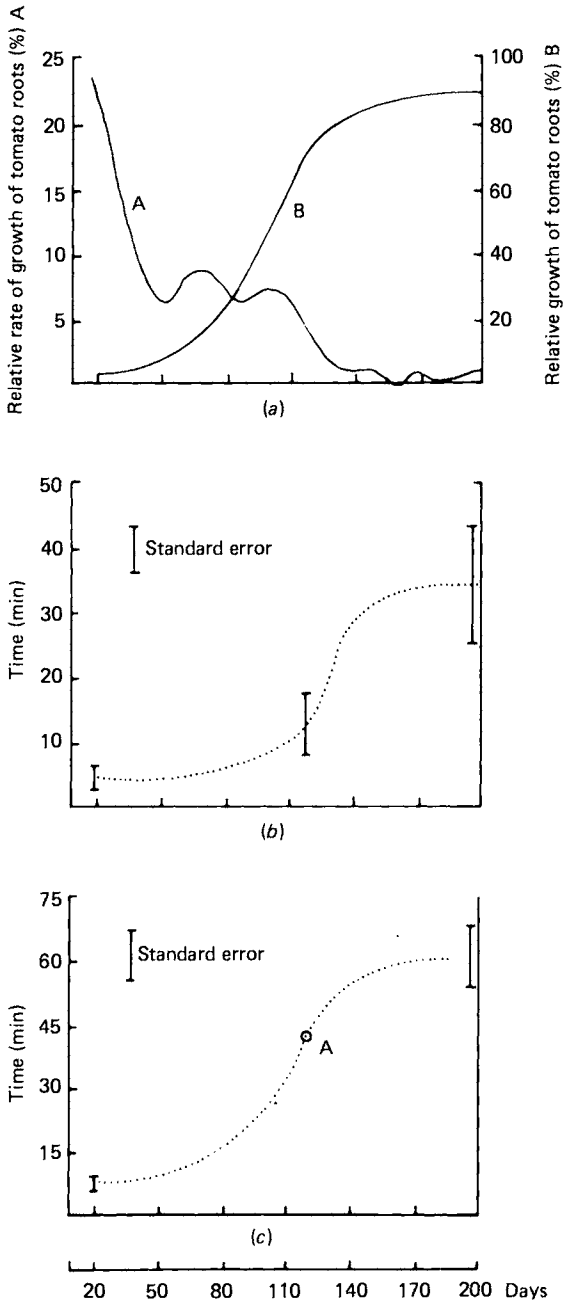


Figure 2.6 Variations in estimated residence time, $\hat{T}$, and transportation time delay, $\hat{t}$, over the growing season, compared with relative growth of plant roots: (a) relative growth of plant roots (after Winsor, Hurd and Price, 1979); (b) estimated $\hat{T}$ values with standard errors; (c) estimated $\hat{t}$ values with standard errors (A is the only data point available for the intermediate period and thus has no error bounds). Dotted lines indicate possible patterns of variation between experimental points. Figures are calculated for 31 m channels

coefficient of determination, R_T^2 , is 0.946, indicating that 94.6% of the data has been explained by the model. The recursive estimation algorithm also provides estimates of the standard errors associated with the parameter estimates, which can be used to compute the standard errors associated with the estimates of the residence time, T , and gain, G , obtained by reference to *Equation 2.4*. If necessary, it is possible to obtain a stochastic model for the noise shown in *Figures 2.3(c)* and *2.5(c)* (i.e. the difference between the model output $\hat{x}_k$ and the measured output), where

$$\hat{x}_k = \frac{\hat{b}_0 z^{-\delta}}{1 + \hat{a}_1 z^{-1}} u_k \quad (2.6)$$

and the 'hat' over a variable indicates its estimated value.

Table 2.1 AGGREGATED DEAD-ZONE MODEL CHARACTERISTICS OVER THE GROWING SEASON

<i>Weeks after sowing</i>	<i>Estimated residence time, $\hat{T}$(s)</i>	<i>Estimated transport delay, $\hat{\tau}$(s)</i>	<i>Length of channel section (m)</i>
4	60–90	135–165	8
17	130–290	630	8
28	200–350	360–570	4

Individual channels are 31 m in total length; *Figure 2.6(b)* and *(c)* refers to $\hat{T}$ and $\hat{\tau}$ values for this total length of channel.

A summary of the complete modelling results is given in *Table 2.1*, which shows the range of estimated parameter values obtained at different stages in the plant growth for 4 and 8 m lengths of channel. The fairly wide range of values for each growth stage is not surprising: it arises because of the considerable non-uniformity of both root growth and flow behaviour at different sections of the channels. However, the general trend of increasing residence times and transportation time delays with growth period is quite obvious and makes reasonable physical sense: clearly the root growth is the main factor in increasing these properties of the ADZ model.

In this latter connection, it is interesting to compare the increases in $\hat{T}$ and $\hat{\tau}$ with the relative growth of the roots, as shown in *Figure 2.6(a)–(c)*. *Figure 2.6(a)*, curve A, shows the relative rate of growth for tomatoes given by Winsor, Hurd and Price (1979), together with the relative accumulated growth (curve B), as obtained by integrating curve A. *Figure 2.6(b)* and *(c)* are plots of the $\hat{T}$ and $\hat{\tau}$ values at the three selected stages in the plant growth (with standard error bounds); the dashed curves are intended merely to illustrate the possible nature of the parameter variation with time, given the shapes of the growth curve in *(a)*. Such variation is, of course, only conjecture since experimentation has been limited to the 4th, 17th and 28th weeks and we do not have estimates for intermediate values of the parameters.

THE DYNAMIC BEHAVIOUR OF THE CATCHMENT TANK

Tracer experiments on the catchment tank (trench) have been carried out recently but totally satisfactory and reproducible results have not yet been obtained.

Consequently, the trench modelling is not complete at this stage of the project. In the NIAE system, the trench is fed by 16 channels situated along its whole length, and approximately 15% of the output flow is recirculated to the upper end of the trench, partly as a means of inducing better mixing. The control solution of nutrient is injected into this return pipe (see *Figure 2.1*). The mixing characteristics of the trench are still not good, however, and some degree of stratification occurs.

It is the lack of good mixing in the trench that has made modelling a little difficult. However, these problems have not delayed control system design, as we shall see *below*. This is because the overall dynamic response of the trench is fairly rapid, as shown in *Figure 2.7(a) and (b)*, which are the graphical plots of the results obtained from two of the tracer experiments on the trench. *Figure 2.7(b)*, in particular, shows the evidence of the recirculation in the second peak, which appears after about 5 min. Although these data have not been analysed fully because of the lack of repeatability, it is clear that the tracer is dispersed reasonably quickly, with a time constant of between 10 and 30 min. This can be compared with residence time plus pure time delay ($\hat{T} + \hat{\tau}$) for the complete channels ranging from 15 min, when there is little root growth in week 4, to 95 min in week 28 of the growing period.

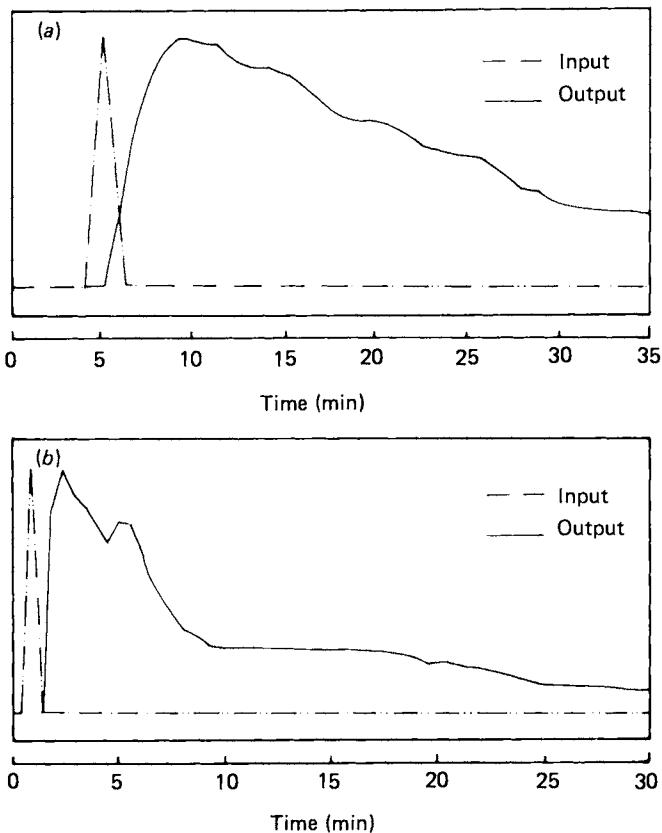


Figure 2.7 Results from two tracer experiments performed on the settling trench: (a) tracer input at far end of trench, output measured at input to circulation pump; (b) tracer input in middle of trench, output measurement as for (a)

NUTRIENT UPTAKE BY THE PLANTS

Very little nutrient is taken up by the plants during a single, limited-time tracer experiment. Consequently, there is little information in the experimental data on which to base estimates of the decay rate, r , in *Equations 2.1 and 2.2*: in effect, the fairly large standard errors on the estimates $\hat{G}$ and $\hat{T}$ of the steady state gain and residence time, respectively, preclude any accurate estimation of the small values of r which characterize the NIAE system for the sampling intervals of interest.

Estimates of r could be obtained from long-term experiments on the NFT system but these have not been possible so far in the project. As a result, we have estimated the possible range of variation of the decay rate on the basis of information in the technical literature on NFT systems. Not surprisingly, the rate of uptake of nutrient ions is highly correlated with light intensity, as shown by Adams and Massey (1984), with correlation coefficients of 0.94 for potassium and 0.91 for nitrogen. Naturally enough, the major nutrient uptake occurs during the daylight hours, as shown in *Figure 2.8* (after Adams and Massey, 1984). It is reasonable to assume that a similar diurnal uptake distribution will occur for the other major ions.

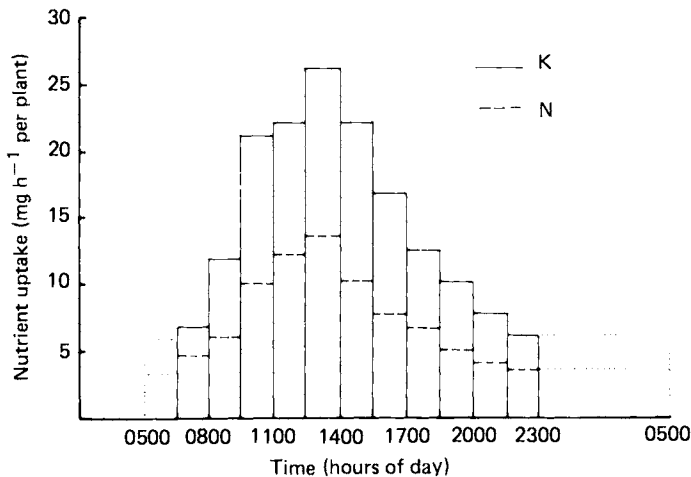


Figure 2.8 Nutrient uptake of tomato plants over a 24h period (after Adams and Massey, 1984). The dotted lines show extrapolations on intuitive grounds

Using *Figure 2.8*, together with information on total plant numbers, total volume of nutrient solution, and the average (i.e. desired) concentration level of potassium ions (400 ppm), it is possible to obtain the results shown in *Table 2.2*. This provides the estimated maximum and minimum nutrient uptake rates per 15 min, together with the associated steady state gain estimates obtained from *Equation 2.2*, using the residence time estimates from *Table 2.1* modified to account for the pure time delay. This modification appears necessary because the nutrient solution is 'resident' in the channels for a period of time equal to the sum of $(T + \tau)$ s. The simple theoretical model does not allow for this in the definition of the ADZ residence time but we can clearly account for the increased exposure of the plants by taking account of the time delay in the $\hat{G}$ estimation.

Table 2.2 ESTIMATED VARIATION IN NUTRIENT UPTAKE RATE r OVER THE GROWING SEASON

<i>Weeks after sowing</i>	<i>Daily uptake (mg per plant)</i>	<i>Max. rate of uptake (per 15 min)</i>	<i>Min. rate of uptake (per 15 min)</i>	<i>Pure time delay + ADZ residence time ($\hat{T} + \hat{\tau}$) (min)</i>	<i>Max. steady state gain, $\hat{G}_{\max}$</i>	<i>Min. steady state gain, $\hat{G}_{\min}$</i>
4	0.71	3.23×10^{-5}	9.2×10^{-6}	10 + 4.5	0.999991	0.99997
17	214	5.27×10^{-3}	1.53×10^{-3}	42 + 13	0.994	0.979
28	229	3.8×10^{-3}	1.1×10^{-3}	60 + 35	0.993	0.977

The large number of decimal places in the first row of *Table 2.2* are included only to show that the uptake rate is very small and the resultant $\hat{G}$ very close to unity. We might expect, however, that the true decay rate will be larger than the values quoted in *Table 2.2*, since there will be losses in the system other than those arising from plant uptake of nutrients. This will lead to somewhat lower steady state gain values than those given in *Table 2.2* and this has been taken into account in the automatic control studies discussed *below*.

Initial thoughts on control system design

The NFT system research project at Lancaster and the NIAE has been concentrated so far on the modelling of the nutrient delivery system, as discussed *above*. But modelling is only a means to an end, in this case the operational control of the NFT system. Following the normal procedures of applied systems analysis, therefore, it has been necessary to consider the implications of the longer-term control system design aspects of the research in both the planning and execution of the project. For this reason, various possible operational control strategies have been investigated in parallel with the glasshouse experiments and associated modelling studies.

SELF-ADAPTIVE AND SCHEDULE-ADAPTIVE CONTROL

As originally conceived, the project was to be concerned with the investigation of adaptive methods in the operational control of glasshouse systems, in particular the NFT process. It was argued that the disadvantages of the existing simple control schemes lay in their inability to avoid some of the inherent problems of NFT cultivation, such as the difficulty in maintaining a satisfactory balance of the ion concentrations in the nutrient solution, as mentioned earlier. It was thought necessary, therefore, to consider more advanced techniques for both measurement and control, including the use of selective ion electrodes and self adaptive control methods.

Computer control of greenhouse climate has received increasing attention in recent years (e.g. Studman, 1984; White, 1984), with applications ranging from computer-based implementation of simple, traditional control procedures, to more sophisticated adaptive control (e.g. Udink ten Cate, 1983 and *Chapter 1*; Davis, 1984). In contrast, NFT control has received little attention, probably because it is economically less important than climate control.

In an adaptive system, it is assumed that the controlled process may undergo changes in its dynamic characteristics, changes which can be either relatively predictable or completely unforeseen, depending upon the application. In such situations, conventional fixed gain automatic control techniques *may* not be sufficient to maintain adequate control over the system, despite the relative insensitivity to changes in the controlled system which is a feature of feedback control. In certain aerospace applications, for example, the system dynamics are known to change as a function of the vehicle's location within its 'flight envelope'. Consequently, 'scheduled gain' methods are often employed, in which the control system gains are continually adjusted in line with the variations in certain 'air-data measurements' that are available from an on-board computer, and provide good information on the current flight régime of the vehicle.

Schedule-adaptive systems are not necessarily appropriate to all circumstances, however, and alternative self-adaptive control (SAC) techniques have been investigated (e.g. Young, 1966, 1980), in which the control system is able to replace completely or to override the predefined gain schedule. Also in recent years there has been considerable interest in 'self-tuning' control systems (see Åström, 1983, for a review of SAC including self-tuning): here the control gains are tuned to provide some 'optimal' performance by means of a computer learning algorithm, usually based on some form of recursive parameter estimation (Young, 1984).

The initial evaluation of the NFT system at NIAE led us to believe that the major variations in the system behaviour that might necessitate SAC were connected with the changes in the nutrient uptake rate by the plants: in the short term due to diurnal effects, and in the long term because of seasonal growth factors. It was also realized, fairly early on, that *very* tight control over the nutrient levels was probably not essential or even desirable, since the natural adaptability of the plants allowed them to grow satisfactorily within certain acceptable ranges of ion concentrations in the nutrient mixture.

With these considerations in mind, the NFT system was originally modelled as a variable gain dynamic process, and the discrete-time, sampled-data control system was designed with the control actuation period chosen to be long in comparison with the dominant time constants of the system. In this situation, the model used for control system design can be in the form of a variable gain element which represents the variations in the steady state gain, G , of the system resulting from the variations in nutrient uptake (see Equation 2.2).

Such a control system will not maintain tight control over the process, because of the coarse control interval, but it should be able to adjust nutrient inputs sufficiently well to ensure an acceptable medium for plant growth. The SAC system designed in this initial phase of the research was based on a state-variable feedback (SVF) pole assignment strategy (see Young and Willems, 1972) with the closed loop poles of the sampled data system assigned at the origin of the complex plane in order to achieve, ideally, 'dead-beat' behaviour (i.e. rapid non-oscillatory response to command and disturbance inputs). The feedback system so designed is extremely simple: it consists of a DDC system with single loop, purely integral action in which the integral control gain is made inversely proportional to the changing steady state gain of the system.

Of course, the SAC system needs to estimate the changing steady state gain continually in order to adjust the integral gain continually. In simulation studies this was achieved by a 'learning' procedure of straightforward design, based on the recursive algorithm for estimating the changing mean value of a random variable

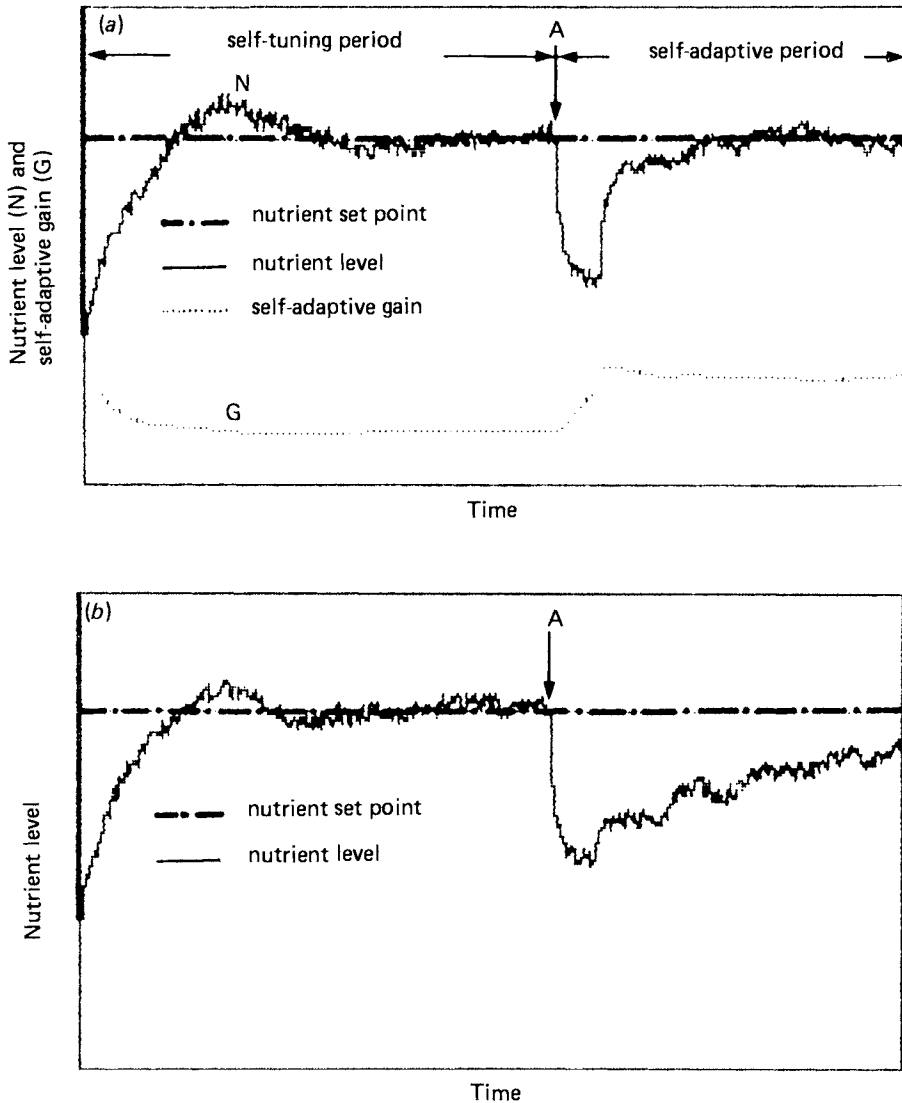


Figure 2.9 Results obtained from simulation of a simple self-adaptive control system for the NFT process. (a) Digital control system with self-tuning and self-adaptation. (b) Conventional digital control system with feedback gain set at the self-tuned level in (a). Point A indicates time at which a large step change in steady state gain (i.e. nutrient uptake rate) occurs

(see Young, 1984). *Figure 2.9* compares the simulated performance of this SAC system with the equivalent fixed-gain controller of similar design. It is clear that even here the self-adaptation is not essential, since the integral action is able to correct for the large change in system steady state gain at time *a* (*Figure 2.9*). However, the SAC system exhibits faster response and the additional complexity of the self-adaptive gain introduces some obvious benefits.

It will be noted that both control systems work well, even with the quite heavy simulated noise and despite the apparent crudeness of the control system structure, i.e. its coarse control actuation interval and single loop integral action. These results are significant in relation to the next phase in the control system design, which was based on our improved knowledge of the system dynamics arising from the continuing modelling studies. It should be noted that the sampling and control strategy used in the above control system designs is of a rather novel type. In particular, the control input signal is updated on the coarse actuation interval (2 h) but the control law itself is based on a much smaller interval (15 min). This will become clearer when we consider an alternative fixed-gain control system, which uses a similar sampling and control strategy.

FIXED-GAIN CONTROL

The SAC system was not discussed in detail *above* because the results of the simulation studies and our growing understanding of the NFT system dynamics made it clear, early in 1985, that fixed-gain control of a slightly more sophisticated type could be adequate for most purposes. Clearly, one does not proceed with a more complicated solution to a problem if a simpler solution is acceptable within the defined objectives. Of course, the results obtained with this fixed-gain control system are still only based on simulation, and it may be necessary to modify the design, possibly by the reintroduction of self-adaptive elements, at a later stage in the research.

The experiments on the NFT system at the NIAE outlined *above* made it clear that the overall nutrient delivery system dynamics are dominated by the inherent positive feedback effects of the pump-driven recirculatory system and the associated high 'forward' gain caused by the low nutrient decay rate, r (arising from the relatively small plant uptake and other losses). Such a high-gain, positive feedback system results in dynamic characteristics which are dominated by a mode of behaviour with a very long time constant, so that the system can appear, in the short term, to be functioning almost as a pure integrator (as it is exactly if $r = 0$). Short-term fluctuations caused by the recirculation are present in the response of the system and these are quite apparent in *Figure 2.7(b)* and the associated computer simulations which we have carried out.

The system with its positive feedback can be simulated with various levels of complexity, of course, and we will be considering a fairly complex simulation in the near future. But such complexity is not fully justified at this stage in the research and we have so far restricted attention to the model shown in *Figure 2.10*. This is a sampled-data, block diagram representation of the system for a sampling interval of 15 min. The forward block, X, represents the settling trench which, for the selected sampling interval of 15 min, can be represented approximately as a unit delay element. This may seem a rather drastic simplification but it will suffice at this stage in the control system analysis when we are rather uncertain about the trench model. In any case, we can examine the sensitivity of the control system to this simplification by subsequent simulation exercises. The feedback block, Y, represents a highly aggregated model of the channel system which has the following general form

$$x_k = \frac{Bz^{-\Delta}}{1 + Az^{-1}} y_k \quad (2.7)$$

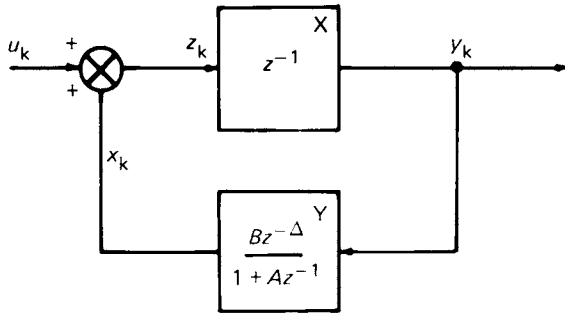


Figure 2.10 Block diagram of simple, highly aggregated transfer function model for NFT process, showing the dominant positive feedback loop. Sampling interval for model is 15 min

where, by comparison with *Equation 2.6*, Δ represents the aggregate transportation delay in the channels; A and B are the model parameters for the whole channel system, which will depend on seasonal factors and changing decay rates; x_k is the nutrient concentration entering the trench; and y_k is the output concentration from the trench. In *Figure 2.10*, u_k is the control input signal (i.e. the metered inputs of nutrient mixture and other control chemicals that directly affect the controlled variable—in this case potassium), and z_k represents the sum of u_k and x_k . Again, the model (*Equation 2.7*), although a highly simplified representation, can be justified for control studies: in effect, we are replacing a multi-order system with time delays by a single first-order delay system whose residence time and time-delay characteristics are ‘equivalent’ to those of the more complex model.

For a ‘typical’ situation in the middle of the growing season, values of $A = -0.63$, $B = 0.3552$ and $\Delta = 3$ appear reasonably appropriate: these values provide for an aggregate residence time, T_a , of approximately 0.5 h; a transport delay, τ_a , of 0.75 h; and associated steady state gain, G_a , of $0.3552/(1 - 0.63) = 0.96$ (i.e. equivalent to a 4% loss of nutrient in the long term). Here we have deliberately chosen both T_a and τ_a to be somewhat larger than we might anticipate from *Table 2.1* in order to ensure that the total lag in the system is not being underestimated.

With the above values for A , B and Δ , the system shown in *Figure 2.10* can be reduced by block diagram manipulation methods to a single transfer function (TF) equation of the following form

$$y_k = \frac{1 - 0.63z^{-1}}{1 - 0.63z^{-1} - 0.3552z^{-4}} u_{k-1} \quad (2.8)$$

where the absence of z^{-2} and z^{-3} terms in the denominator of the TF is the main effect of the channel transport delay and the associated positive recirculating feedback. When the system is simulated, however, the *longer term* response characteristics, for a *longer sampling interval* of 2 h, can be represented more simply by a first-order TF of the form

$$y_k = \frac{1.4z^{-1}}{1 - 0.944z^{-1}} u_k \quad (2.9)$$

This simpler model has the same steady state gain (25) as the system in *Equation 2.8* and a time constant of some 140 sampling intervals: its main deficiency as a

model of the system is its inability to reproduce the short-term perturbations caused by recirculation, but these are of much less importance at the 2 h control interval on which we will now base the control system design.

If the SVF pole assignment procedure of Young and Willems (1972), as used in the adaptive studies, is applied to the model (*Equation 2.9*), it yields the DDC system block diagram shown in *Figure 2.11*, where CI represents the desired set point level (or command input). This will also be recognized as a proportional plus integral (PI) control, with K_p and K_I representing the proportional and integral feedback gains, respectively. For a dead-beat specification similar to that used in the adaptive system, the control gains are computed to be $K_p = 0.67$ and $K_I = 0.71$ and the resulting simple two-term control law can be written in the following discrete-time terms, where the sampling interval is 15 min and the control actuation interval is 2 h (8×15 min),

$$u_k = u_{k-1} + K_I(CI - y_k) - K_p(y_k - y_{k-1})$$

for $k = 0, 8, 16, \dots$, and

$$u_k = u_{k-1}$$

for all other k , $0 \leq u_k \leq u_{\max}$.

The control constraints are imposed to avoid excessive demands that can be generated by the dead-beat specification, particularly during start-up when the control error ($CI - y_k$) is large.

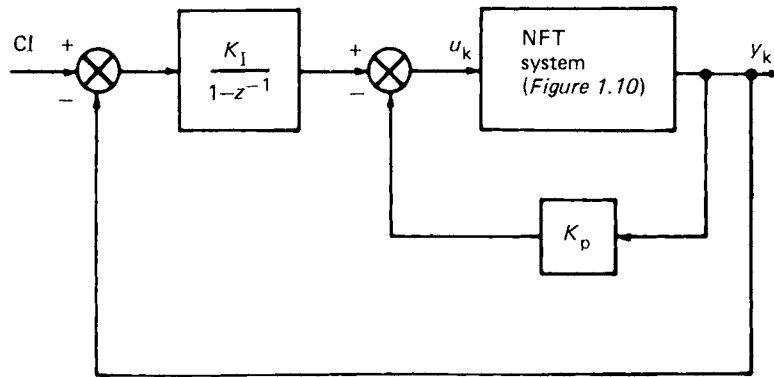


Figure 2.11 Block diagram of fixed-gain, direct digital control (DDC) system for the NFT process shown in *Figure 2.10*. Control actuation interval is 2 h but control law is based on 15 min sampling interval

The DDC system described above is rather unusual because of both its coarse control actuation interval and the apparently tight specification used in the SVF design. But simulation experiments suggest that the combination of these two characteristics yields remarkably robust control performance. These simulation experiments utilized the NFT model shown in *Figure 2.10* with a 15 min sampling interval but with the control action applied on the coarser 2 h interval appropriate to the above analysis.

Figure 2.12 shows the response of the simulated system with $B = 0.369$ and $A = 0.63$, i.e. with $G_a = 0.997$ and only a 0.3% loss of nutrient, so that the system is

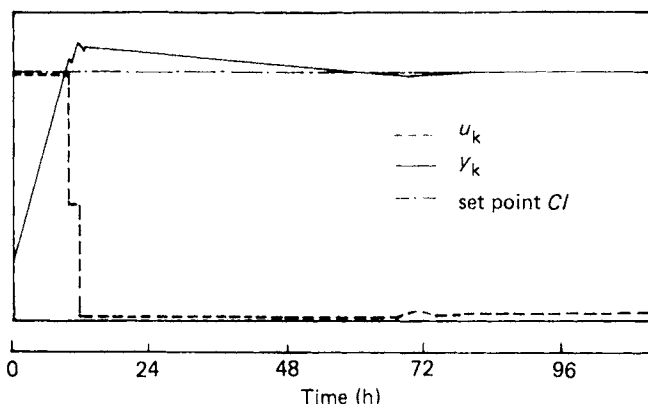


Figure 2.12 Results obtained from simulation of DDC system shown in *Figure 2.11* for the case where there is little nutrient uptake by plants and no nutrient losses

functioning almost as an integrator. Even in these conditions, the control system maintains excellent control with a smooth increase to the desired set point level during start-up, a small overshoot, and a gradual decay to the set point. Clearly, the inability of the system to generate negative control inputs inhibits its response time in this difficult situation, but the performance is still quite satisfactory given the system requirements.

Figure 2.13(a)–(c) illustrates the behaviour of the controlled system when the steady state gain, G_a , is varied sinusoidally with a 24 h period and an amplitude such that the nutrient loss varies between zero and 6% (in order to simulate crudely the effects of diurnal variations in plant uptake). *Figure 2.13(a)* shows the basic response of the controlled system and demonstrates its ability to keep the nutrient concentration at the set point despite the changing dynamics of the NFT process. The response remains satisfactory even when stochastic disturbances are added to the system, as shown in *Figure 2.13(b)*; although the noise effects are clearly visible, the nutrient concentration levels remain acceptable over the whole 112.5 h simulation period. If the feedback gains are doubled in relation to the design values (i.e. $K_p = 1.34$; $K_I = 1.42$), the deterministic simulation results are even better, as shown in *Figure 2.13(c)*; on the other hand, the noise rejection is not so good, although the behaviour is still acceptable.

Figure 2.14(a)–(c) demonstrates the performance of the controlled system with the doubled feedback gains and nutrient loss pattern similar to that used in *Figure 2.13*, but with different time delays, Δ , associated with the channel system, of 4, 8 and 12 sampling intervals (i.e. 1, 2 and 3 h), so simulating crudely differences either in the channel characteristics or in the recirculatory pumping rate. Although this variation in the transportation delay is much greater than current experimental results suggest will be encountered in practice, the control system performance remains quite acceptable. The main detrimental effect is the longer initial time taken for the system to achieve the set point level (i.e. the start-up time).

These initial simulation results, although limited in scope, suggest that the NFT process can be controlled by a DDC system with a fairly coarse sampling interval of 2 h and a fixed-gain, two-term PI controller. At this stage it does not seem necessary to utilize any adaptive mechanism, since this special fixed-gain design seems remarkably resilient to any changes in the NFT system dynamics. Also, at

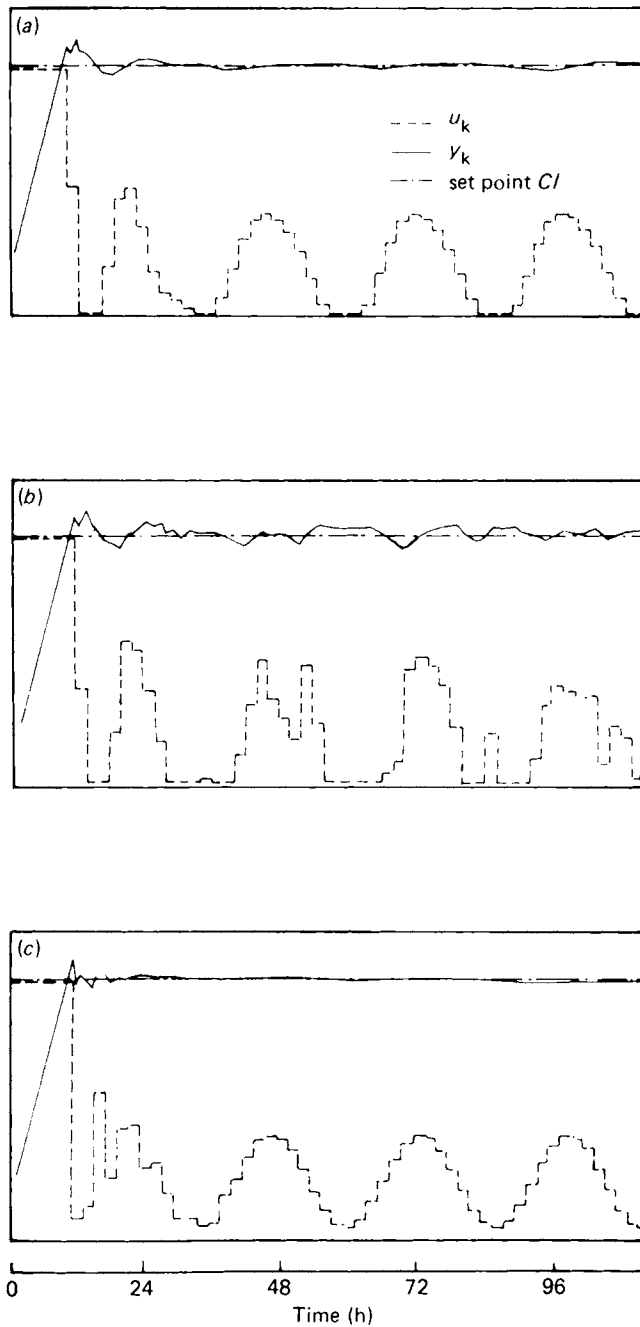


Figure 2.13 Results obtained from simulation of DDC system shown in *Figure 2.11* when diurnal changes in nutrient uptake are occurring: (a) basic response; (b) response with stochastic disturbances added to system; (c) response when the proportional and integral control gains are doubled

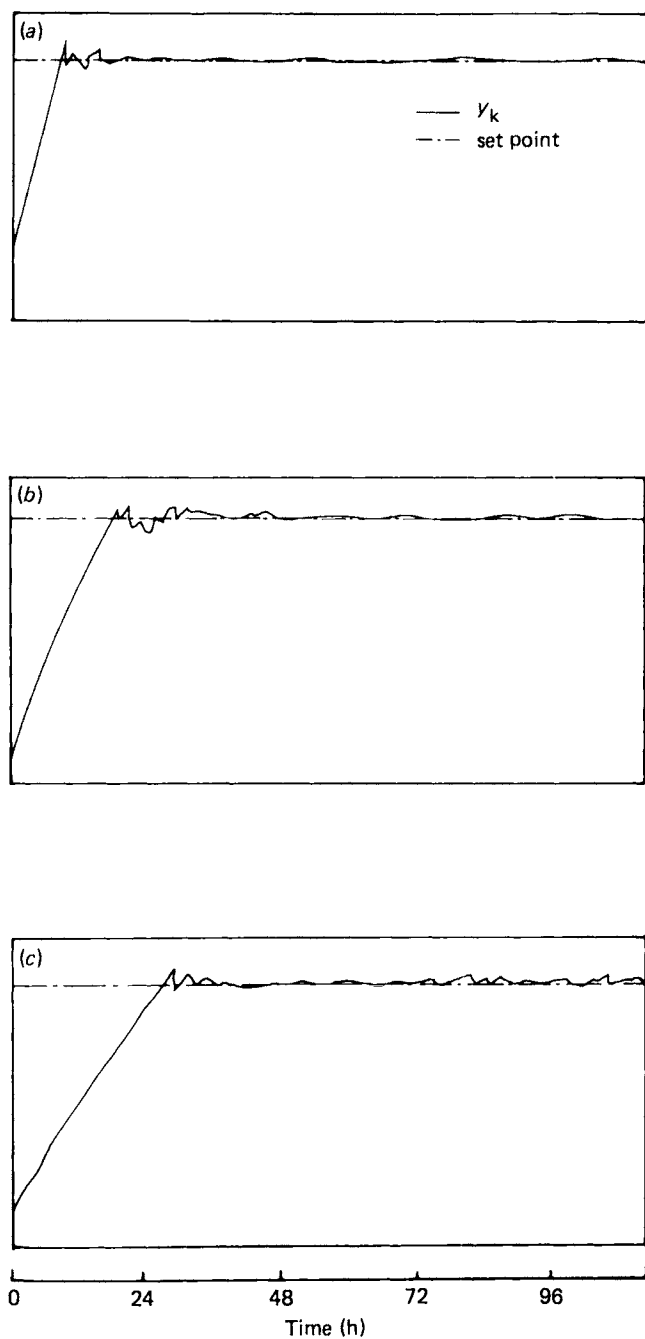


Figure 2.14 Results obtained from simulation of DDC system shown in *Figure 2.11* when the transportation time delay is changed over a wide range of values and the nutrient uptake pattern is similar to that in *Figure 2.13*: (a) $\tau = 4$; (b) $\tau = 8$; (c) $\tau = 12$

this stage there do not appear to be any major foreseeable problems associated with practical implementation of the controller, although some difficulties will undoubtedly emerge when its practical design is pursued further, both by simulation and during testing on the NFT system at NIAE during 1985. Recent simulation experiments, for example, have utilized a more detailed model of the NFT system, with both the channels and the trench represented by higher-order models. However, these experiments have yielded similar results to those obtained with the simpler model.

Finally, it is interesting to compare and contrast the above results, as well as those obtained with an alternative SAC system discussed *above*, with the results of Åström (1984). Åström considers the control of salt concentration in a similar recirculatory system to the NFT (at laboratory scale) and uses a self-tuning implementation of the linear, quadratic, gaussian (LQG) type of feedback control system. He demonstrates that self-adaptation is necessary to maintain control of the system over a range of different flows. However, his control actuation period is much smaller, relative to the system time delay plus time constant, than that used here.

Conclusions

The Nutrient Film Technique (NFT) offers the possibility of better control over the quality and production of certain glasshouse crops such as tomatoes. In this paper, we have described the results obtained during the first year of a joint University/Research Institute study of the NFT system. This has involved an investigation of the dynamic behaviour of an experimental NFT process, with the object of eventually designing an operational DDC system which will avoid some of the previous difficulties encountered with NFT cultivation.

Although the short-term dynamics of the NFT process are dominated by the recirculating nutrient delivery system, and may change radically with plant growth, the medium-term dynamics appear fairly straightforward. Consequently, fixed-gain DDC of relatively novel but simple design seems to provide the possibility of robust operational control performance. Simulation studies indicate that this control system is resilient to both the short-term changes in system dynamics that occur because of diurnal changes in nutrient uptake, and the long-term changes arising from root growth over the growing season.

So far, the control studies have been limited to simple analysis and computer simulation; also they have been concerned only with single variable control of the individual nutrient ions, such as potassium. Later results obtained from the more detailed simulation model shown in *Figure 2.15* have confirmed the simpler simulation results. Future research will culminate in practical evaluation, together with further development of the DDC system on the NFT process at the NIAE. More sophisticated multi-variable control, possibly with self-adaptive adjustment, will be considered if the simpler control system design is not fully satisfactory.

It is well known that considerable improvements in control performance can be obtained if any dynamic interactions between the controlled variables are taken into account and, if possible, exploited. The design and implementation of such multi-variable control systems requires multi-loop coordination and would be capable of fully exploiting the virtues of an ion-selective electrode measurement system. However, as with adaptive control, it can add considerable complexity and is only really justified if simpler techniques prove unsatisfactory.

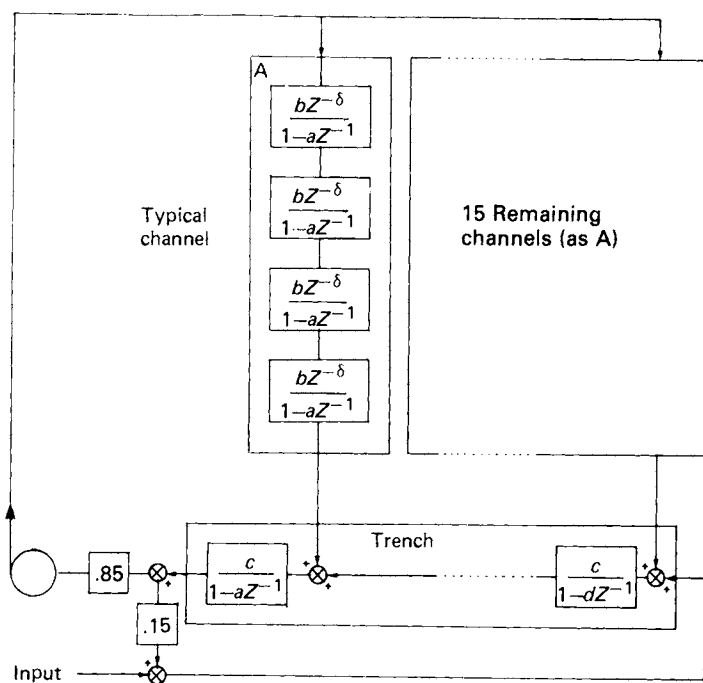


Figure 2.15 High-order simulation model of the NFT system at the NIAE. Each channel is represented as a serial connection of four ADZ elements and the settling trench is modelled as eight ADZ elements, with the channel flows entering between each element

Acknowledgements

All the experimental work described in this chapter was carried out at the National Institute of Agricultural Engineering. The authors would like to acknowledge the considerable assistance given to the project by the staff at NIAE. They are particularly grateful to Dr Bernard Bailey for all his help in the planning of the experiments and to Dr Brian Legg, Glasshouse Department, for his continual encouragement. The assistance of the technical staff in the Department of Environmental Science at the University of Lancaster, particularly Ken Reid, Charles Blakeley and John Place (who designed the EPSON data logger), is gratefully acknowledged.

References

- ADAMS, P. and MASSEY, D.M. (1984). Nutrient uptake by tomatoes from recirculating solutions. In *Proceedings, 6th International Congress of Soilless Culture, Lunterer, Netherlands, 29 April–5 May, 1984*. International Society for Soilless Culture.
- ÅSTRÖM, K.J. (1983). Theory and application of adaptive control: a survey. *Automatica*, **5**, 471–486

- ÅSTRÖM, K.J. (1984). LQG self tuners. In *Adaptive Systems in Control and Signal Processing*, pp. 137–146. Ed. by Landau, I.D., Tomizuka, M. and Auslander, D.M. Pergamon, Oxford
- BEER, T. and YOUNG, P.C. (1983). Longitudinal dispersion in natural streams. *American Society of Civil Engineers Journal of Environmental Engineering*, **109**, 1049–1067
- CHATFIELD, C. (1984). *The Analysis of Time-Series: An Introduction*, 3rd edn. Chapman and Hall, New York
- COOPER, A.J. (1967). Tiered trough and nutrient film methods of tomato growing. *Annual Report of the Glasshouse Crops Research Institute*, p. 59
- DAVIS, P.F. (1984). A technique of adaptive control of the temperature in a greenhouse using ventilator adjustments. In *Proceedings, Agricultural Engineering '84 Conference, NIAE, Cambridge*. Academic Press, London
- GRAVES, C.J. (1983). The nutrient film technique. *Horticultural Reviews*, **5**, 1–10
- STARKY, N. (1979). Yield and quality not in the bag. *Grower*, **92** (18), 19
- STUDMAN, C.J. (1984). Protected cropping research in Northern Europe. *Growing Today*, **1**, 21–25, 50
- UDINK TEN CATE, A.J. (1983). 'Modelling and adaptive control of greenhouse climates'. PhD thesis, Agricultural University, Wageningen
- WHITE, R.A.J. (1984). From switches to computers. *Growing Today*, **1**, 26–30
- WINSOR, G., HURD, R.G. and PRICE, D. (1979). The nutrient film techniques. *Glasshouse Crops Research Institute, Grower's Bulletin*, **5**, 2nd Edition.
- WINSOR, G. and MASSEY, D. (1978). Some aspects of tomatoes growing in recirculating solution. *Acta Horticulturae*, **82**, 21–132
- YOUNG, P.C. (1966). Process parameter estimation and self adaptive control. Proceedings, IFAC Symposium, Teddington. In *Theory of Self Adaptive Control Systems*. Ed. by Hammond, P.H. Plenum Press, New York
- YOUNG, P.C. (1978). A general theory of modelling for badly defined systems. In *Modeling, Identification and Control in Environmental Systems*, Ed. by Vansteenkiste, G.C. North Holland, Amsterdam
- YOUNG, P.C. (1980). A second generation adaptive autostabilization system for airborne vehicles. *Automatica*, **17**, 459–470
- YOUNG, P.C. (1984). *Recursive Estimation and Time-Series Analysis: An Introduction*. Springer Verlag, Berlin
- YOUNG, P.C. (1985). The instrumental variable method: a practical approach to identification and system parameter estimation. In *Proceedings, IFAC Symposium on Identification and System Parameter Estimation*, Ed. by Young, P.C. and Barker, A. Pergamon, Oxford
- YOUNG, P.C. and WILLEMS, J.C. (1972). An approach to the linear multivariable servomechanism problem. *International Journal of Control*, **15**, 961–979

THE USE OF A PET MICROCOMPUTER IN RAINFALL INTERCEPTION STUDIES OF HEATHLAND

R.L. HALL

Institute of Hydrology, Wallingford

Introduction

The effects of afforestation of Scottish catchments on their water yield is of concern to the water industry and the subject of research at the Institute of Hydrology. Realistic modelling of these effects requires accurate information concerning the rate at which intercepted precipitation is evaporated from canopies, for both coniferous forest and the indigenous vegetation, predominantly heather, which the forest is replacing. The Penman–Monteith equation (*see below*) is often used to calculate the rate of evaporation from wet vegetation; however, before the equation can be used it is necessary to know the appropriate value of one of its terms, r_v , the aerodynamic resistance to water vapour transfer, for the particular vegetation type. Several workers have determined values of r_v for coniferous forest (e.g. Rutter, 1967; Stewart and Thom, 1973; Robins, 1974; Calder, 1977) but until recently little useful information concerning r_v was available for heather. The system described here has now provided the required information.

CALCULATION OF THE RATE OF INTERCEPTION LOSS

The Penman–Monteith equation (Monteith, 1965) for wet canopies assumes that the water source can be considered as a single layer and that the evaporative flux (λE) is one-dimensional and given by

$$\lambda E = \frac{\Delta H + \rho c_p (q' - q)/r_v}{\Delta + c_p/\lambda} \text{ W m}^{-2} \quad (3.1)$$

In this equation, $H = (R_n - G)$ is the energy flux density (W m^{-2}) available for partition between sensible and latent heat; R_n is the net radiation flux density; G is the soil heat flux density; q and q' are the specific humidity and the saturated specific humidity of the air (kg kg^{-1}), respectively; Δ is the slope of the saturated specific humidity *versus* temperature curve at air temperature ($\text{kg kg}^{-1}\text{K}^{-1}$); ρ is the density of moist air (kg m^{-3}); c_p is the specific heat of air at constant pressure ($\text{J kg}^{-1}\text{K}^{-1}$); λ is the latent heat of vaporization of water (J kg^{-1}); and E is the

evaporation rate ($\text{kg m}^{-2}\text{s}^{-1}$). The aerodynamic resistance to water vapour transfer to some reference height is defined by

$$r_v = \frac{\rho(q'_s - q)}{E} \text{ s m}^{-1} \quad (3.2)$$

where q'_s is the saturated specific humidity at the temperature of the wet surface.

Therefore, to use *Equation 3.1* in interception models for the estimation of the evaporation rate from wet heather, data sets of certain meteorological variables are required, together with an appropriate value of the aerodynamic resistance for heather. The system described *below* was designed primarily to provide that information by measuring the rate of evaporation and the environmental variables necessary for solving *Equations 3.1* and *3.2* for r_v over a range of windspeeds.

Equipment

The system shown in *Figure 3.1* was designed to be portable, so that *in situ* measurements could be made at a variety of sites. A Pet 4032 microcomputer interrogates a Sartorius 3806MP electronic balance, which monitors the evaporative loss of mass from a sample of vegetation supported by the top 100 mm of soil, and concurrently interrogates an array of meteorological sensors which monitor the prevailing weather. The Pet and associated electronics and peripherals are kept in a caravan and the entire system is powered by a portable generator.

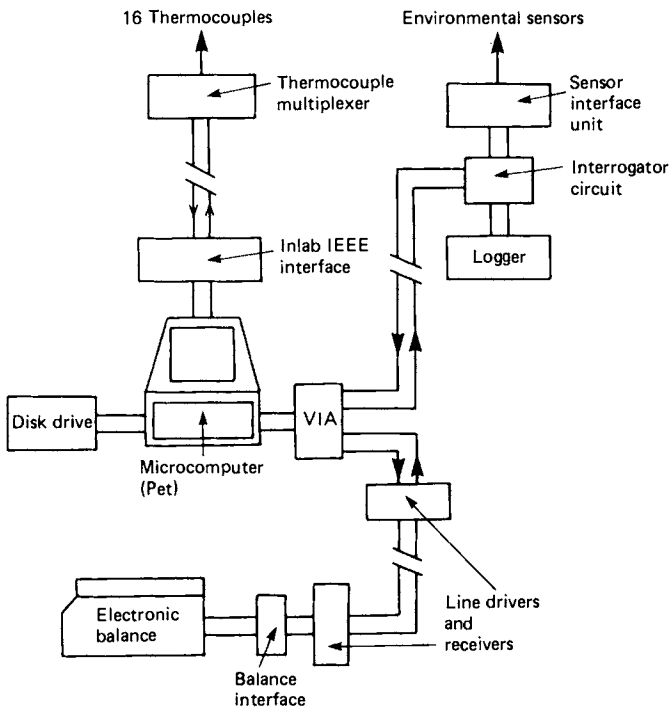


Figure 3.1 A schematic diagram of the complete system

To interrogate both the balance and the meteorological sensors an extra input/output port was required on the Pet (it was supplied with only one parallel user port). To provide this a Versatile Interface Adaptor (VIA, MOS Technology chip number 6522) was attached to the memory expansion connector. The VIA is a flexible and powerful device, having two input/output ports controlled by 16 programmable registers accessed by four address lines. The configuration of the input/output ports used for interrogating the sensors and the balance is given in *Appendix 3.1*.

The memory-mapped architecture of the Pet makes addressing the VIA simple but does require that a block of 16 bytes of memory is dedicated to it. Memory locations at hexadecimal addresses 8C00 to 8C0F (35840 to 35856 in decimal) were chosen as convenient, being immediately above the locations used for the screen memory and below the memory designated for ROM expansion. The hardware involved in addressing the VIA is minimal, since complete decoding is unnecessary. The binary representation of the address of register 0 (8C00) of the VIA, given *below*, shows the address connections required.

Hexadecimal	8	C	0	0				
Binary	1 0 0 0	1 1 0 0	0 0 0 0	0	0	0	0	
Pet bus lines	<u>SEL8</u>	11 10		3	2	1	0	
VIA pins	CS2	CS1		A3	A2	A1	A0	

The four VIA register select lines (A0 to A3) are connected directly to the Pet bus address lines 0 to 3. Of the two VIA chip select pins, one of them, CS2, is connected directly to the Pet line SEL8, which carries the select signal for addresses within the 4k byte block between 8000 and 8FFF. The remaining chip select pin, CS1, is connected through simple decoding (a 7400 chip is used; *see Figure 3.2*) to lines 10 and 11 on the Pet address bus, to be activated when both go high. Further decoding is unnecessary because no other devices have addresses between 8C0F and 8FFF, the remaining bytes of the 4k block. As shown in *Figure 3.2*, all the remaining signal pins of the VIA are connected to their corresponding lines on the Pet bus. Pin 1 is connected to the system earth and pin 20 to a stabilized 5 V supply provided by a 7805 regulator connected to a 12 V laboratory power supply.

For convenience of programming, both VIA ports are used; port A for interrogating the balance and port B for interrogating the sensors. The Pet's parallel user port is free for other applications. The bit configuration of the two ports (*see Appendix 3.1*) is different, being dictated by the control line and data transmission requirements of the devices attached to them. Twelve-core cable with an earthed sheath is used for connecting all of the equipment in the field to the Pet.

MEASUREMENT OF EVAPORATION

A commercially supplied interface connected to the balance enables the Pet to initiate and monitor weighing and ensures that the different data transmission rates of the balance and Pet are matched through the use of four 4015 shift registers. Line drivers (75113) and receivers (75115), between the VIA and the balance interface, are employed at each end of the signal lines to prevent degradation of the signals during transmission down the cable (100 m in length) due to line capacitance. The drivers and receivers are contained in two waterproof boxes with their own stabilized 5 V supplies.

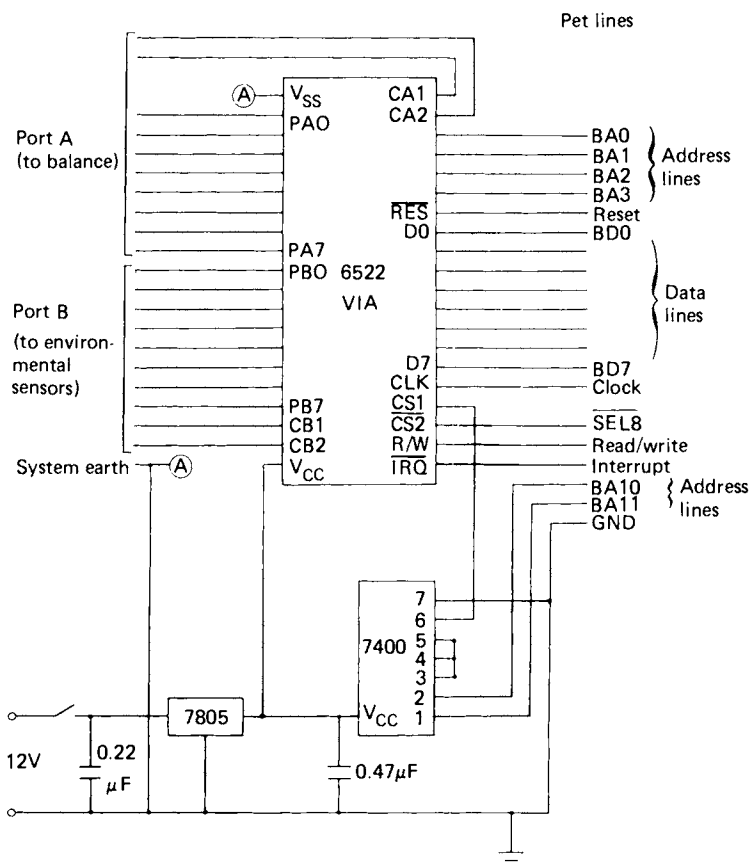


Figure 3.2 The pin connections and decoding between the Pet microcomputer and the 6522 VIA chip

The Sartorius 3806MP balance has a maximum capacity of 30 kg with an accuracy of 1 g; for the area of sample used this is equivalent to a depth of 0.003 mm of water. To protect the balance from dirt and moisture it is housed in an aluminium box with a neoprene rubber top; a breather arrangement enables it to function normally. When *in situ*, the box rests in a pit on a levelling frame with three adjustable legs so that samples of vegetation, held in a glass fibre tray on top of the balance, are flush with the surrounding vegetation. More details of the box and tray are given in Calder *et al.* (1984).

MEASUREMENT OF THE PREVAILING WEATHER AND SURFACE TEMPERATURE

Meteorological variables are monitored using a system based on an Automatic Weather Station (AWS) manufactured by Didcot Instruments Ltd (Strangeways, 1972). A standard AWS uses a 12-channel Microdata M200L incremental data logger and M200U universal transducer interface unit. These are retained to

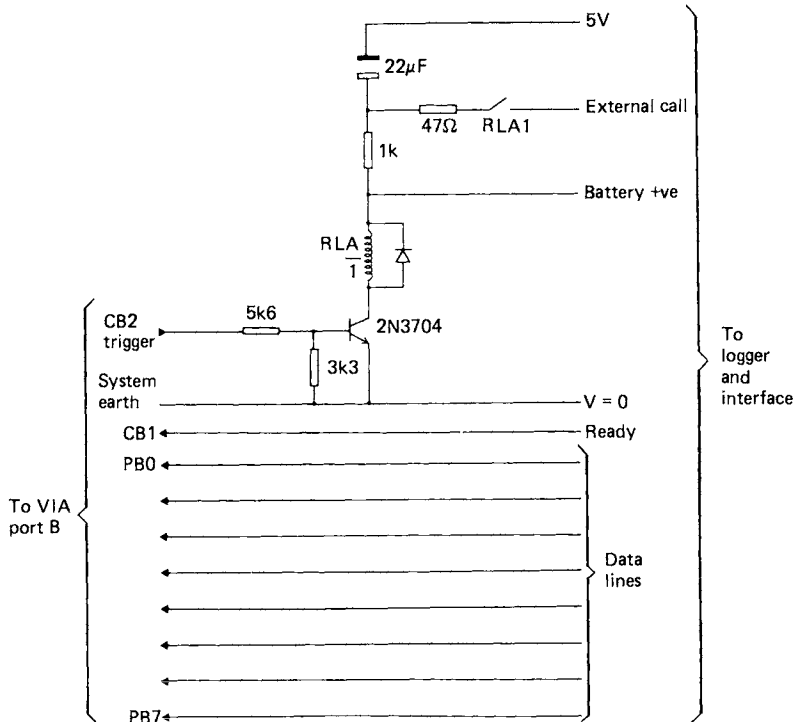


Figure 3.3 The interrogator circuit used to enable the Pet to trigger and monitor the Microdata logger and interface

provide an analogue-to-digital convertor and multiplexer. However, to enable the logger to be triggered externally by the Pet, the internal clock of the logger is disconnected and the interrogator circuit shown in *Figure 3.3* connected between the logger and interface unit: the cassette tape which stores the data on a standard AWS is dispensed with. Line drivers and receivers are unnecessary because of the relatively low rate of data transmission.

Sensors are changed readily, requiring only that the relevant board in the interface unit is exchanged. Typically, the variables measured and the sensors used are: air temperature and wet-bulb depression at 1.2 m above the ground, using an aspirated psychrometer with platinum resistance thermometers; wind run, measured at 2 m above the ground, and net radiation, measured using two radiometers (Funk type). A diaphragm pump provides a stream of air, dried by silica gel, to keep the radiometer domes inflated and free from condensation. The surface temperature of the vegetation is also measured with bead thermistors calibrated against a precision mercury-in-glass thermometer in a stirred water bath.

Sixteen miniature thermocouples (K type, 0.127 mm wire) were later added to the system to improve the accuracy of the surface temperature measurement by reducing the sampling error and by achieving better thermal contact with the heather than is possible with the thermistors. The thermocouples are connected to a 16-channel multiplexer and conditioning card (Signatrol TC5022K) housed in the field in a waterproof box with its own stabilized power supply. The analogue output of the thermocouple amplifier is fed through a relay, closed only when the

Table 3.1 METEOROLOGICAL VARIABLES MEASURED

<i>Meteorological variable</i>	<i>Precision (or accuracy if indicated)</i>
Net radiation	5% or 5 W m^{-2} , whichever is greater
Depression	0.1 K accuracy
Air temperature	0.1 K accuracy
Surface temperature	0.1 K
Windspeed	0.2 m s^{-1}

thermocouples are selected, to the analogue line of a 3D Inlab system. This is connected to the IEEE 488 bus of the Pet and provides for up to 256 single-ended analogue inputs which are processed through a 12 bit analogue-to-digital convertor.

The soil heat flux has not generally been measured; however, this should not cause any significant errors in the determination of the available energy since Oliver (1982), measuring soil heat flux beneath heather at Berner's Heath in Norfolk, found that it never exceeded 5% of the net radiation flux.

Table 3.1 summarizes the variables measured, with their associated precision.

Operating the system

The system has been used at various grass and heather sites within Britain but the procedure at each has been the same. Evaporation rates from representative samples of fully wetted vegetation were measured after either rainfall or artificial spraying, together with the prevailing weather. An algorithm of the system program is shown in *Figure 3.4*. The Pet interrogated the meteorological sensors at 1 min intervals and the balance at approximately 1 s intervals. The mass readings were filtered as described *below* and the filtered values, together with the meteorological data, were stored on disk for later analysis.

Calculations

Measurements of the mass of the sample contain a random element due to the variable vertical component of the wind forces acting on the sample. The microcomputer has made possible the reduction of this noise through software filtering techniques. These comprised either a simple arithmetic mean calculated over the interval between scans of the meteorological sensors or a low-pass autorecursive filter, the software equivalent of an RC circuit. The low-pass filter takes the form

$$y(i) = Zy(i-1) + (1-Z)m(i)$$

where $y(i)$ and $m(i)$ are the filtered and unfiltered masses at time i , and Z is the feedback factor which takes a value between zero and one. It can be shown (*see, for example, Otnes and Enochson, 1972*) that the output from this filter is a running mean where k , the effective number of data values being averaged, is determined according to the relation

$$k = -(1.4 \ln Z)^{-1}$$

Z was chosen so that $k = 35$, typically the number of weighings occurring between sensor scans.

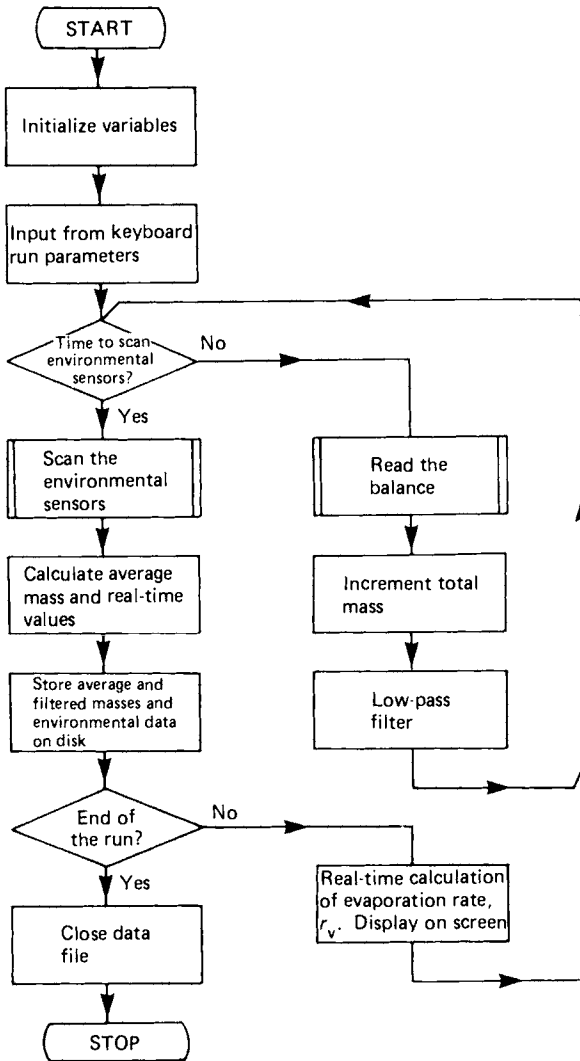


Figure 3.4 A flowchart of the program used to control the system

Additional filtering was used in off-line calculations to reduce remaining low-frequency noise. A linear 11-point moving average (see Kendall, 1973) was found to give good results. The filtered masses were used to calculate average evaporation rates from the wet heather canopy which, with averaged meteorological data, were used to solve *Equations 3.1* and *3.2* for the aerodynamic resistance. More details of the off-line analysis are given in Calder *et al.* (1984).

Results

Figure 3.5 shows 20-min averages of a set of data acquired on 21 September 1982 at Berner's Heath in Norfolk immediately after a frontal rainstorm of about 15 mm.

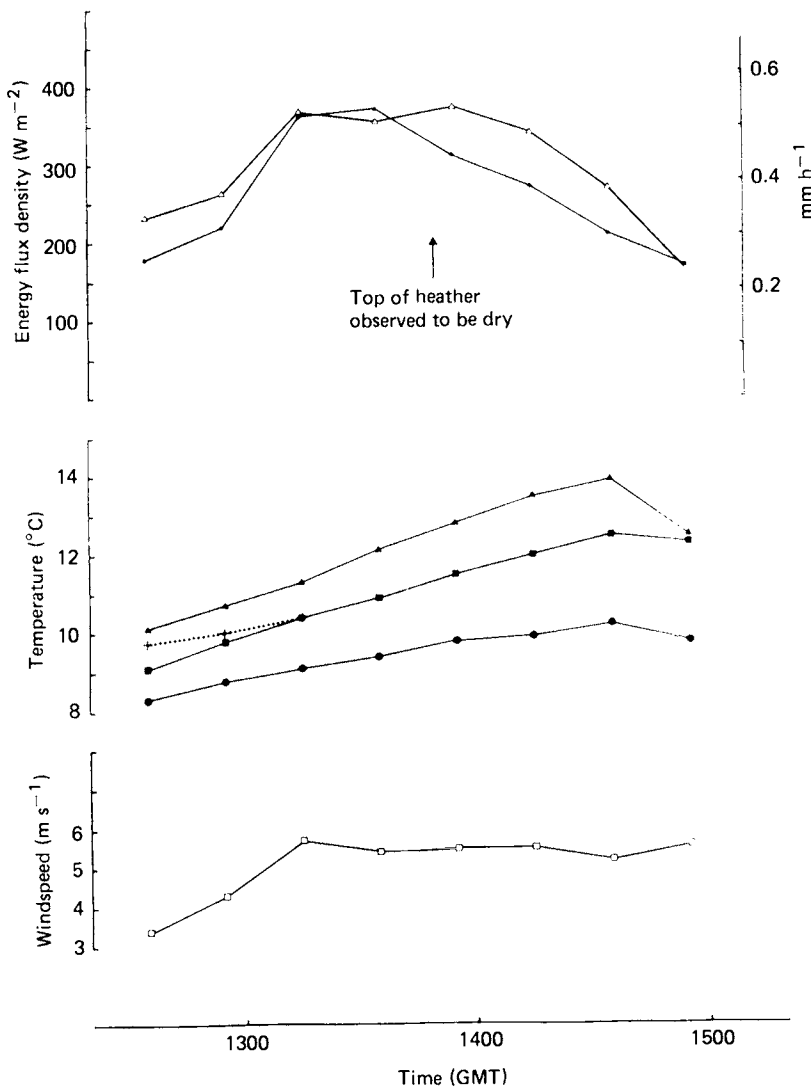


Figure 3.5 Twenty-minute averages of data collected by the system between 1220 and 1500 GMT on 21 September 1982 at Berner's Heath, Norfolk. Key: —●— latent heat flux density; —△— net radiation flux density; —▲— surface temperature; —■— dry-bulb temperature; —●— wet-bulb temperature; —□— windspeed;+..... theoretical surface temperature, T_s . T_s was calculated for the period when the heather was wet using, $T_s = T_d + r_h(R_n - \lambda E)/\rho c_p$ ($^{\circ}\text{C}$), where T_d is the air temperature and r_h is the aerodynamic resistance to heat, assumed equal to R_v calculated from Equation 3.1

During the first 55 min there was an increase in the windspeed and in the latent heat flux until this equalled the net radiation, i.e. all the available energy was used for evaporation. After about 80 min and a total of 0.6 mm evaporation, the latent heat flux began to decrease and the sensible heat flux to increase as a result of the drying of the heather canopy, observed visually at 1350 GMT. Over the same period, there was a gradual increase in the wet-bulb depression, air and surface temperatures and in the difference between the air and measured surface temperatures. There is an indication that the measured surface temperatures were systematically too high. When the sensible heat flux was zero (between 1315 and 1340 GMT) the air and

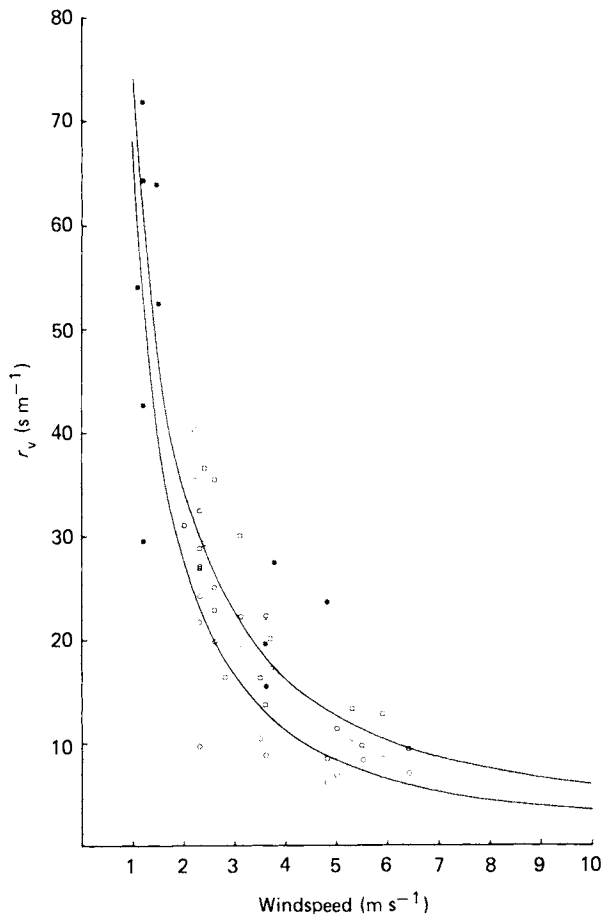


Figure 3.6 The aerodynamic resistance to water vapour transfer from wet heather plotted against windspeed at 2 m height, from data collected at Berner's Heath in Autumn 1982. Values of r_v calculated using *Equation 3.1* and *Equation 3.2* indicated by circles and squares respectively. Open symbols denote that the data were collected after the heather was sprayed; closed symbols denote that the data were collected after rainfall. The two curves indicate the functions $r_v = 68u^{-1.3} \text{ sm}^{-1}$ and $r_v = 74u^{-1.1} \text{ sm}^{-1}$, fitted to the resistances denoted by the circles and squares, respectively: see also *Table 3.2* and the text.

surface temperatures should have been the same; however, the measured surface temperature exceeded the air temperature by about 1 K, probably through a combination of solar heating of the sensors and poor thermal contact between them and the heather. A theoretical surface temperature, calculated for the period when the heather was wet, has also been plotted in *Figure 3.5*.

Aerodynamic resistances calculated from data collected at Berner's Heath in Autumn 1982 are plotted against windspeed in *Figure 3.6*. These data clearly show a windspeed dependence, but also a small systematic difference between the values calculated using *Equations 3.1* and *3.2*. It is most likely that the higher values of r_v determined from *Equation 3.2* are the result of the overestimation of the surface temperature. Resistances calculated from data sets collected after rainfall or spraying have been shown by analysis of variance not to be significantly different at the 5% level.

Table 3.2 THE AERODYNAMIC RESISTANCE AS A FUNCTION OF WINDSPEED AT DIFFERENT LOCATIONS

Site	The coefficients C and indices i of the function $r_v = Cu^i$			
	calculated from Equation 3.1		calculated from Equation 3.2	
	C	i	C	i
Berner's Heath	68 ± 11	-1.3 ± 0.3	74 ± 8	-1.1 ± 0.15
Moormore	44 ± 9	-1.1 ± 0.2	51 ± 8	-1.0 ± 0.1
Killin	20 ± 2	-0.6 ± 0.06	33 ± 2	-0.8 ± 0.05

A linear regression analysis of $\ln r_v$ on $\ln u$, where u is the windspeed at 2 m above ground, for the two sets of resistances calculated from *Equations 3.1* and *3.2* gave the first two functions in *Table 3.2* as the best fits. Despite the systematic difference, these equations agree to within one standard error. The same regression analysis applied to data from two Scottish sites, Moormore (near Aviemore) and Killin, has yielded the remaining functions in *Table 3.2*. For comparison, the functions fitted to resistances calculated using *Equation 3.1* have been plotted in *Figure 3.7* for the three different sites. This shows that for windspeeds less than 5 m s^{-1} the resistances for Killin are less than those for Moormore which, in turn, are less than those for Berner's Heath. These differences probably reflect differences in the topography of the three sites: the site at Killin was on a hillside with very rough local topography, at Moormore the locality was less rough and gently sloping, and at Berner's Heath the site was very flat and level in all directions for a large distance (at least 0.5 km). There were also differences in heather cover, but the results of Calder et al. (1984) suggest that these are unlikely to be the cause of different resistance functions. It seems likely that the additional turbulence associated with rough topography produces an increase in the efficiency of water vapour transfer, reflected in reduced resistances.

Conclusions

A Pet microcomputer has been applied, after the provision of two additional input/output ports by means of a VIA, to the monitoring of environmental variables and evaporation rates. These data, after suitable averaging and filtering, have been used in *Equations 3.1* and *3.2* to calculate the aerodynamic resistance as a function of windspeed. The portability of the system has made possible the determination and comparison of the resistance for a variety of heather sites.

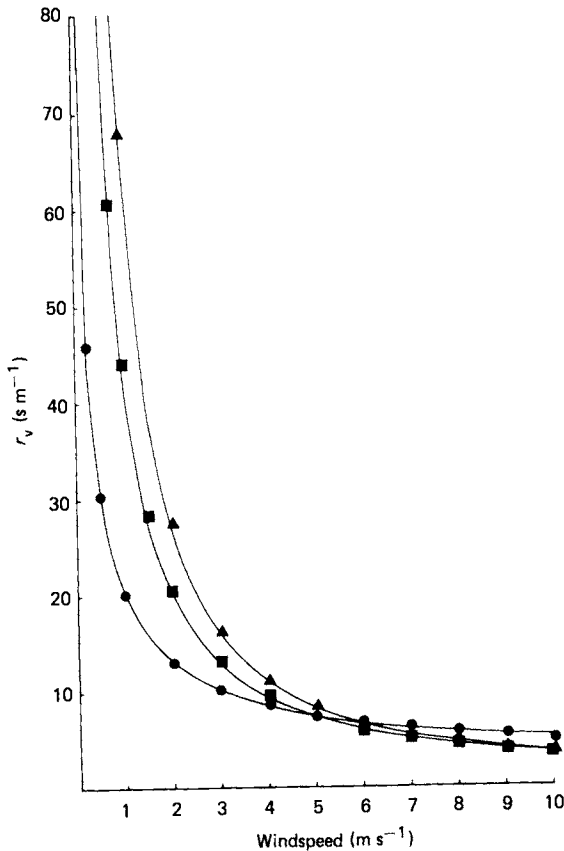


Figure 3.7 The aerodynamic resistance as a function of windspeed at different sites derived from resistances calculated from *Equation 3.1*. —▲— denotes the function $r_v = 68u^{-1.3} \text{ s m}^{-1}$, fitted to r_v values for Berner's Heath; —■— denotes the function $r_v = 44u^{-1.1} \text{ s m}^{-1}$, fitted for Moormore; —●— denotes the function $r_v = 20u^{-0.6} \text{ s m}^{-1}$, fitted for Killin.

The incorporation of an infra-red thermometer into the system would allow improved measurement of surface temperature.

Acknowledgements

I am most grateful for the help of other members of the Institute of Hydrology, viz. Ian Calder, Richard Harding, Ivan Wright and Steve Edwards.

I am also grateful to the constituent members of the Scottish Consortium on Upland Afforestation* who funded the work, to Mr Grant for permission to work on the Rothiemurchus Estate, to the Earl of Iveagh for permission to work on the Elveden Estate and to Mr W.M. Sloan, the estate manager, for his cooperation.

*British Waterways Board, Department of Energy, Department of the Environment, Forestry Commission, North of Scotland Hydro-electric Board, Scottish Development Department, Water Research Centre.

References

- CALDER, I.R. (1977). A model of transpiration and interception loss from a spruce forest in Plynlimon, central Wales. *Journal of Hydrology*, **33**, 247–265
- CALDER, I.R., HALL, R.L., HARDING, R.J. and WRIGHT, I.R. (1984). The use of a wet-surface weighing lysimeter system in rainfall interception studies of heather (*Calluna vulgaris*). *Journal of Climate and Applied Meteorology*, **23**, 461–474.
- KENDALL, M.G. (1973). *Time Series*. Griffin, London
- MONTEITH, J.L. (1965). Evaporation and the environment. In *The State and Movement of Water in Living Organisms*. 19th Symposium of the Society for Experimental Biology, pp. 205–234
- OLIVER, H.R. (1982). Some aspects of the water and energy balances of vegetation. In *Proceedings International Symposium on Hydrological Research Basins and their Use in Water Resources Planning*, Vol. 2, pp. 229–238. *Sonderheft, Landeshydrologie*. Office Fédéral de la Protection de l'Environnement, Bern
- OTNES, R.K. and ENOCHSON, L. (1972). *Digital Time Series Analysis*. Wiley Interscience, New York
- ROBINS, P.C. (1974). A method of measuring the aerodynamic resistance to the transport of water vapour from forest canopies. *Journal of Applied Ecology*, **11**, 315–326
- RUTTER, A.J. (1967). An analysis of evaporation from a stand of Scots pine. In *Forest Hydrology*, Ed. by Sopper, W.E. and Lull, H.W. pp. 403–417. Pergamon Press, Oxford
- STEWART, J.B. and THOM, A.S. (1973). Energy budgets in pine forests. *Quarterly Journal of the Royal Meteorological Society*, **94**, 44–55
- STRANGEWAYS, I.C. (1972). Automatic weather stations for network operation. *Weather*, **27**, 403–408

Appendix 3.1

The direction and function of the eight input/output lines on VIA port A connected to the electronic balance are as tabulated *below*.

<i>Line number</i>	<i>Direction relative to the Pet</i>	<i>Function</i>
PA0	INPUT	Data bit 0
PA1	INPUT	Data bit 1
PA2	INPUT	Data bit 2
PA3	INPUT	Data bit 3
PA4	INPUT	balance ready
PA5	OUTPUT	enable weigh
PA6	OUTPUT	read word
PA7	OUTPUT	read character
The handshake lines CA1 and CA2 are unused.		

Port B, connected to the logger of the meteorological sensors, is configured so that all eight lines, PB0–PB7, are input (data) lines and handshake lines CB1 and CB2 are used as a logger ready and logger trigger, respectively.

MONITORING SOIL WATER CONTENT

D.M. CRANSTON, T.A. JULIAN, PETER NEWTON and SABAH SHAFFI
AL-HADI

University of Manchester, UK

Introduction

We have developed, over the past few years, a method for monitoring soil water content *in situ* by capacitance determination, which has some advantages over the resistance block technique. Measuring soil water content by capacitance determination is not a new idea, but only a limited number of publications are concerned with the technique (e.g. Anderson and Edlefsen, 1942; Anderson, 1943; de Plater, 1955) compared with the much larger number that deal with measurement using resistance blocks, for example the series of papers by Bouyoucas published between 1940 and 1962 (*see* Bouyoucas, 1962). The introduction of solid state integrated circuits now makes it possible to measure capacitance much more easily and with greater reliability than in the past and therefore one major limitation to soil water measurement has been removed. Clymo and Gregory (1975) published a circuit diagram for a temperature-stable instrument that they suggested might be used for the determination of soil water content. However, they did not describe a sensor and had only used the method to measure the height of the water table in peat bogs (Clymo, personal communication).

The instrument

After preliminary trials with wires of different thicknesses and from different sources, we have chosen to use a sensor based on 16 s.w.g. enamelled copper wire with a thinner tinned copper wire wrapped helically along its length (Al-Hadi, Julian and Newton, 1985). In operation there is a change of capacitance between the two wires, related to the changes in moisture in the soil in which they are buried. Water has a much higher dielectric constant than air (80:1), so an increase in moisture, displacing air in the soil, produces an increase of self-capacitance. Conversely, a reduction in soil moisture reduces the capacitance. The self-capacitance of the sensor in dry soil is about 70 pF, and is the capacitance between the thinner wire and the area of enamelled wire close to it. In saturated soil a film of moisture, which is conductive, connects the thinner wire to the whole of the surface area of the enamelled wire. The plates of the sensor capacitor are the enamelled

wire and the moisture film. The enamel coating is the dielectric. The capacitance of the sensor in saturated soil is about 1100 pF, but as the saturated soil gets progressively drier the moisture film in contact with the sensor becomes discontinuous and the meter reading is then determined by a combination of soil dielectric constant and resistance. Eventually, the amount of water present becomes sufficiently small and the resistance sufficiently high for the change of sensor self-capacitance to be due solely to the change of dielectric constant of the soil between the thinner wire and the surface area of the enamelled wire adjacent to it.

An instrument based on the circuit diagram suggested by Clymo and Gregory gives a linear indication of the value of the self-capacitance of the sensor and, unlike resistance blocks and the published methods described to measure soil moisture by capacitance measurement, there is, for a sensor buried in soil, a substantially linear relation between meter reading and soil water content. Typical responses to soil moisture content of the capacitance measurements for three contrasting soils have been published by Al-Hadi, Julian and Newton (1985).

Comparative results

To illustrate the difference between soil moisture measurements made with soil tensiometers (of the type described by Webster, 1966), resistance blocks (supplied by Crump Scientific Products) and capacitance sensors, some laboratory measurements have been made on a sandy clay loam soil taken from the top 10 cm of the Jodrell Bank Experimental Grounds of the University of Manchester. Two boxes of 83 l capacity, 17 cm deep, were used; one box was filled to give an initial

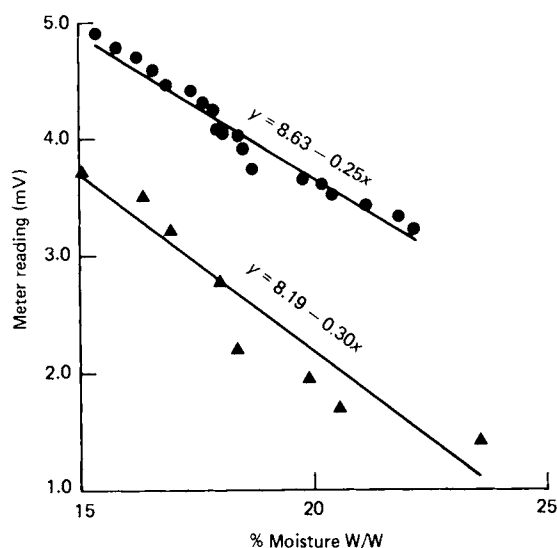


Figure 4.1 Capacitance meter readings *versus* soil moisture percent for soil with bulk density of 1.61 (▲) and 1.08 (●) g cm⁻³

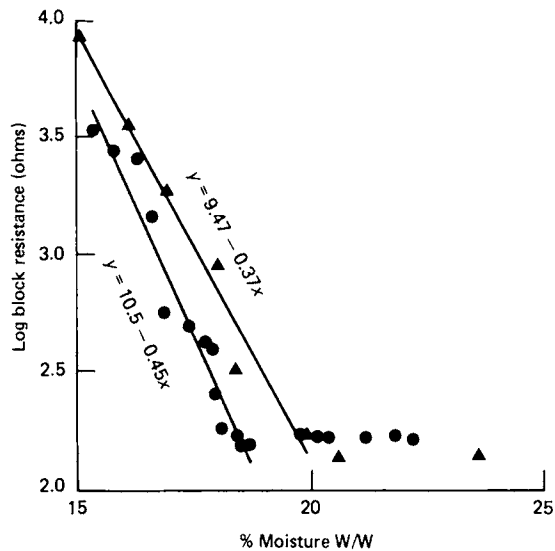


Figure 4.2 Gypsum block resistance *versus* soil moisture percent for soil with bulk density of 1.61 (▲) and 1.08 (●) g cm⁻³

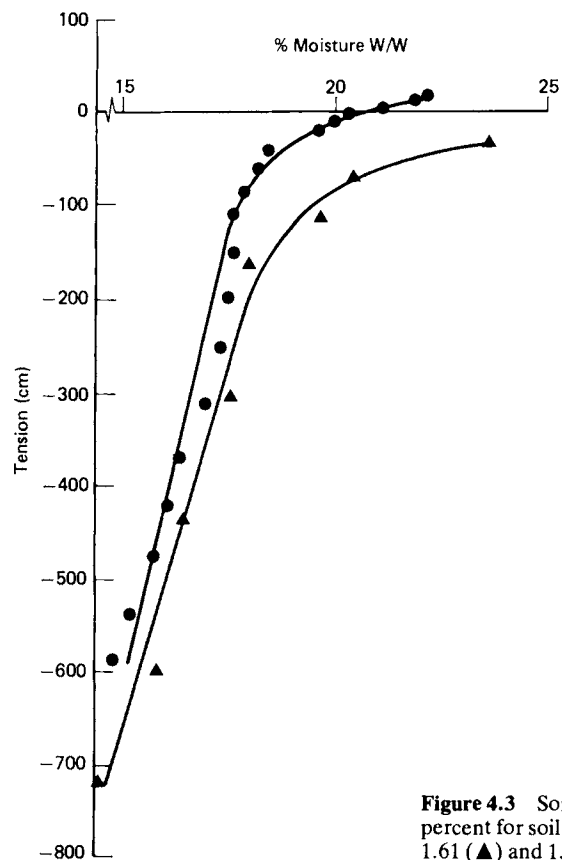


Figure 4.3 Soil water tension *versus* soil moisture percent for soil with bulk density of 1.61 (▲) and 1.08 (●) g cm⁻³

bulk density of 1.08gcm^{-3} , the other to give a bulk density of 1.61gcm^{-3} . Both boxes were filled to within 2cm of the top and the sensors were covered by 5cm of soil. There was an effect of soil bulk density on the readings obtained for tension, resistance and capacitance (*Figures 4.1, 4.2 and 4.3*). There is an obvious improvement in accuracy of soil moisture determination by the capacitance sensors at high soil water content. Calibration will be necessary for each soil, and for any one soil for the different bulk densities resulting from changes brought about by cultivation. However, calibration of the capacitance sensor need only necessitate the determination of two points to fix the regression line, e.g. for 'wet' and 'dry' soil. It may also be possible to calculate the position or slope of the regression line, due to the effect of soil bulk density, when more information is available about the effect of soil bulk density on the performance of the sensor.

There are small effects of soil conductivity and soil temperature on the meter readings. These have been shown to be of the order of 10% for change in soil temperature from 5 to 25°C and 10% for change in soil conductivity from 0.1 to 2.0mS cm^{-1} (Al-Hadi, 1984). There was some effect on the soil water content in the region of a buried sensor as a result of the disturbance when digging a hole to 'plant' the sensors in the field in 1984, but none in 1983 (*Table 4.1*).

Table 4.1 THE EFFECT OF 'PLANTING' SENSORS IN THE FIELD ON SOIL WATER PER CENT (GRAVIMETRIC DETERMINATIONS)

	Soil near sensors	Soil away from sensors	LSD ($P = 0.05$)
1983	20.2	20.3	0.32
1984	14.9	14.1	0.74

For several years we have monitored soil water content by manual measurements, but only with small field plots. A set of measurements made 'by hand' in 1983, initially from 42 sensors buried 10, 20 and 30cm deep in the field at Jodrell Bank Experimental Grounds, shows how meter readings changed in response to rainfall and periods of dry weather (*Figure 4.4*). Spring wheat was

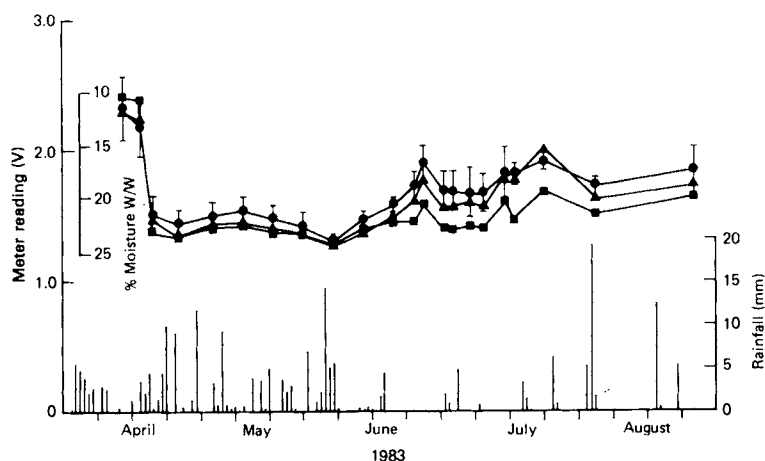


Figure 4.4 Soil moisture measurements, 1983. ●, ▲ and ■ are capacitance meter values for 10, 20 and 30 cm depths, respectively. For the sake of clarity, standard errors are shown for the 10 cm depth only. Vertical lines on the x axis represent rainfall

being grown at the time. The number of sensors was reduced during the growing season as periodic plant and soil samples were taken. A regression equation derived from these soil samples and associated meter readings has been used to convert the meter readings (x) to soil moisture percentage (y). The regression equation was $y = 3.44 - 0.09x$ ($F = 67.4$, 23 DF).

With large plots, where it was not possible to reach sensors in the middle of a plot without damaging the plants, we connected 300ohm, radio-frequency, flat twin cable to each sensor and to a rotary switch, but the low self-capacitance of the cable was significantly increased by rain and high relative humidity, and meter readings were seriously affected. To overcome this problem, we provided each of 12 sensors with its own electronics housed in a small weatherproof box; a four-wire cable carried the necessary low voltage supply to each box, as well as carrying the signal generated by the sensor. This method seemed to work satisfactorily, therefore we extended it to 52 sensors in 1984. In order to minimize loss of data through sensor or component failure we used slightly larger boxes, each with two sensors and two sets of circuitry. The boxes were wrapped in aluminium foil to reflect solar radiation and polythene bags to protect them from rain. The sensors were 'planted' 10, 20 or 30cm deep, uniformly spaced in an area of soil 56 m $\times$ 14 m. Sensors to be recorded (by hand) were 'planted' along the edges of the plot. The whole area was sown with spring wheat.

The outputs from the sensor circuits, which were adjusted to be in the range 1–5 V, were connected to a data logging system based on a Datab Microcontroller (V82/1.5), which was programmed to print out the sensor readings each hour. The microcontroller, which was developed by Oxford University Engineering Laboratories, uses a modified CONTROL BASIC, DUEL/WSL CB Version F2, and has a printed circuit board connected to the main computer and keyboard unit. It has eight addressable slots. Into each slot there can be either: (1) a single analogue-to-digital input port, e.g. Ferranti Z80P10 with an LM324N operational amplifier conditioning the input signal; or (2) an 8 bit digital input/output port, e.g. Z80P10, with the eight ports buffered by L2003 Darlington arrays. The multiplexer used was a 4051B of the COMOS 4000B series, controlled by four logic (0 or 1) signals, three of which selected one of the eight possible switches to be closed and the fourth of which was an enable signal which turned the multiplexer on, allowing a signal to pass. It was therefore possible to control five multiplexers from each 8-channel output port, the three select signals being common to the five multiplexers and the enable signals being used to select a particular multiplexer. To avoid non-linearity at low signal levels, small reed relays were used (Hamlyn CPRI/C), operated by the multiplexer.

Conclusions

Generally, agreement of manual and recorded data has been satisfactory. However, a comparison between the meter readings made by hand and those recorded by the data logger showed a large discrepancy after rain had fallen (*Figure 4.5*). It is probable that rain falling on the polythene bag used to cover the boxes had drained from the cover down the supporting stem and into the soil in the region of the sensors. The supports for the boxes must, obviously, be arranged to prevent this from happening. One further refinement that could be of value would be to separate the outputs from the two sensors from a given box to two separate data

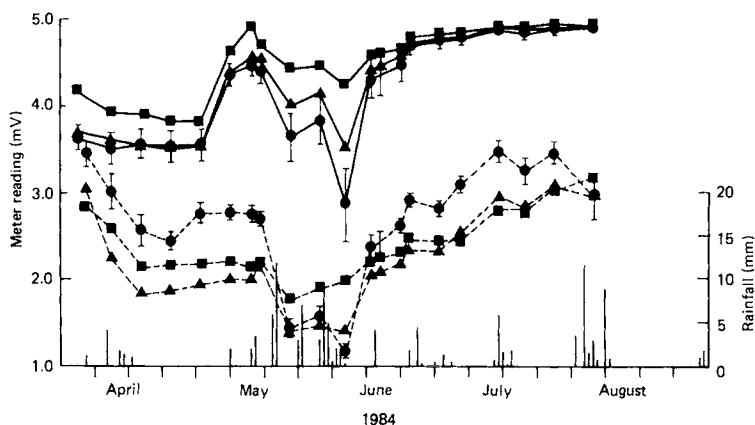


Figure 4.5 Soil moisture measurements, 1984. ●, ▲ and ■ are capacitance meter values for 10, 20 and 30 cm depths, respectively. Solid lines show measurements made 'by hand'; broken lines show measurements obtained from the data logger. Standard errors are as in Figure 4.4. Vertical lines on the x axis represent rainfall

loggers in case there is a failure of one computer interface or printer. In future we are aiming to use Sinclair Spectrum computers with a multiplexing system devised by Harley Systems Ltd, based on 4051B multiplexers, in conjunction with a Harley Systems ADC8-2 Input Module.

Copies of the meter circuit diagram and information about the sensors can be obtained from Peter Newton.

References

- AL-HADI, S.S. (1984). 'The relationship between soil water content and water use by plants.' MSc Thesis, University of Manchester
- AL-HADI, S.S., JULIAN, A.T. AND NEWTON, P. (1985). A capacitance soil moisture meter. *Acta Horticulturae*, **171**, 75–82
- ANDERSON, A.B.C. (1943). A method of determining soil-moisture content based on the variation of the electrical capacitance of soil, at a low frequency, with moisture content. *Soil Science*, **56**, 29–41
- ANDERSON, A.B.C. AND EDLEFSEN, N.E. (1942). Laboratory study of the response of 2- and 4-electrode plaster of paris blocks as soil-moisture content indicators. *Soil Science*, **53**, 413–428
- BOUYOUCAS, G.J. (1962). A continuous electric soil moisture recorder. *Agronomy Journal*, **54**, 549
- CLYMO, R.S. AND GREGORY, S.P. (1975). Two cheap temperature stable, battery-operated devices producing a current linearly proportional to capacitance or resistance. *Journal of Applied Ecology*, **12**, 577–586
- DE PLATER, C.V. (1955). A portable capacitance-type soil moisture meter. *Soil Science*, **80**, 391–395
- WEBSTER, R. (1966). The measurement of soil water tension in the field. *New Phytologist*, **LXV**, 249–258

PRACTICAL CONSIDERATIONS FOR COMPUTER-BASED ENVIRONMENTAL CONTROL OF GLASSHOUSES

S.W. BURRAGE

University of London, UK

Introduction

In the 1970s a number of workers carried out experiments in computer control of glasshouse environments (Takakura, 1973; Van de Vooren, 1975; Bot and Dixhoorn, 1978). Advances since that time include adaptive control (Udink Ten Cate and Van de Vooren, 1978) and distributed systems (Weaving, 1980). The high cost of energy and the potential savings which computer systems offered resulted in a rapid introduction of computer control into the glasshouse industry. By 1982 there were over 1000 systems in operation. There are now over 2000, and computer control is normally an integral part of any new glasshouse installation. Several factors have influenced the rate at which systems have been installed, principally the uniformity of glasshouse structures, which makes installation simple, and a close proximity between operator and installer, to enable a rapid response when problems arise. The majority of systems installed are in the Netherlands where the high density and uniformity of glasshouse structures has been ideal for the establishment of companies offering installation and service facilities. In the UK, where the industry is more varied and widely scattered, the installation of computer systems has been somewhat slower.

A wide variety of systems have been developed and most operate around a permanently pre-programmed EPROM which can only be altered by the supplier. Some systems have been developed using a standard microcomputer (Burrage, 1981) where the program is in BASIC. *Figure 5.1* gives an outline of the architecture which is standard to most systems. The links between sensors, interface, computer and controls are generally made with multicore cable. A single computer may be used, centrally placed, with sensor and control wires for each glasshouse radiating out from the centre—often called a ‘star’ system. Alternatively, each glasshouse may have its own individual ‘slave’ computer which is linked to a central ‘host’ computer through a serial data link (RS232 or 422/423 or 20 mA loop); this is generally termed a ‘distributed’ system. The majority of the systems at present installed are of the ‘star’ type, being considerably cheaper to install where the glasshouse-to-computer distance is small. However, the steady reduction in computer costs is leading to greater development of the distributed systems which need only two or three wires to link the system to the central controller, simplifying and lowering the cost of installation. Also, data transmitted in digital form are less

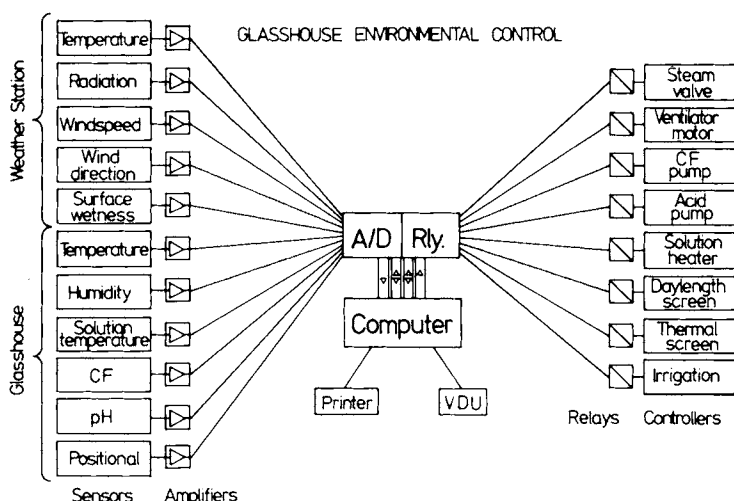


Figure 5.1 System architecture for a computer-controlled glasshouse

susceptible to electrical interference and can therefore be transmitted over longer distances (up to 1 km). Finally, each house can be operated independently, even in the absence of the central host computer.

A wide range of sensors may be used in glasshouse control, including those for temperature, humidity, carbon dioxide, pH, conductivity, radiation, windspeed, wind direction, surface wetness and positional indication. Measurements of boiler temperature, pressure, water flow and level may be monitored for alarm and energy efficiency calculation.

The analogue-to-digital conversion interface provides the link between computer and sensors, converting coding in analogue signals from the sensors to a digital format to allow computer interpretation of the data. A relay interface links the computer with the control circuitry. The control actuators are less varied and are generally relays and proportional controllers. These are linked to pumps, valves and motors of various forms.

One of the major reasons for installing a computer system in preference to conventional analogue controllers has been the ability to integrate environmental factors and thereby to achieve more precise control. The computer can also carry out complex calculations accurately, e.g. for irrigation requirements. Changing the set points, alarm levels and the parameters within the equations from the keyboard of the computer is straightforward and accurate. An added advantage of a computer system is the ability to record, store and display environmental data. This provides useful information for the operator and enlarges the potential use of the system. Information provided can assist in performance monitoring and management decisions.

In this chapter I shall look at the various parts of a computer control system and comment in the light of our own experience and the broader context of systems in general.

Measurements within the glasshouse

A wide range of sensors are used in glasshouse control and present a number of different problems. What is generally required is an accurate durable sensor with

minimal maintenance. The problems that arise can be both electrical and mechanical. Most sensors require amplification or attenuation to fit the input characteristics of the analogue-to-digital converter (ADC). This is best carried out in close proximity to the sensing element to minimize electrical noise on the connecting wires. Duplication of sensors is often advisable to permit reference checks to be made and thereby maintain accuracy of readings. Regular maintenance of sensors, e.g. topping up the water reservoir and wick changing of a psychrometer, will be neglected unless made very simple. Failure to take this into account will inevitably result in inaccurate readings.

TEMPERATURE

Most control systems relate to air temperature and it is thus probably the most important measurement made. The sensor most commonly used is the stainless steel sheathed platinum thermometer (Pt100) although thermistors, thermocouples, diodes and silicon sensors are also used. Sampling is generally on a 1 min cycle, although this may differ with the specific requirements of a house and, on occasions, different sensors may be sampled at different intervals. The response time of the sensor must relate to the sampling frequency used. Sensors are mounted in an aspirated screen for protection against radiation error and ventilation of the wet-bulb thermometer. Aspiration also results in a larger volume of air being sampled.

Control is usually operated from a single point and the choice of sampling point can be very difficult where large variations in temperature exist across a house. It is probably better to survey the glasshouse periodically with a hand-held thermometer to ascertain temperature distribution and to correct any anomalies by changing heating pipe distribution, rather than to take readings from several sensors and different positions in the house and use an integrated value. It may be advantageous for management purposes to monitor several areas of the house with the computer while only operating control from one point. Dual sensors may be used, with the temperature readings from each sensor being compared and a cautionary alarm sounded when the readings deviate by more than a predetermined value, e.g. 1°C. This gives a greater confidence in the readings and the system as a whole.

HUMIDITY

Humidity control is generally secondary to temperature control and in glasshouses humidity is often observed rather than controlled. High humidities are a problem during the winter and spring, when the conflict between energy retention and lowering of humidity generally goes in favour of retaining energy. With the development of dehumidification techniques, more serious attention may be paid to humidity control and a need for accurate humidity sensing will become necessary.

The most commonly used sensor is the psychrometer. In practice, the maintenance of the water level in the reservoir and periodic changing of the wick is often neglected and errors occur in the readings. It is possible to reduce the risk of this by use of a liquid level detector on the water reservoir, which activates an alarm

on the computer when water levels fall below a preset value. Capacitance humidity sensors for humidity measurement have the attraction of low maintenance but, in the past, drift at high humidities and susceptibility to contamination have restricted their use. A number of new sensors have been developed that are not quite so susceptible to these problems. I have had success in the glasshouse with the 'Valvo' sensor manufactured by Philips in the Netherlands. However, these sensors have not been so successful in mushroom sheds where high humidities are maintained over long periods by the injection of steam. There is considerable scope for the development of a reliable, low-maintenance humidity sensor, perhaps an infra-red device. At the present time, it would appear that the psychrometer is still the most reliable, provided it is well maintained.

CARBON DIOXIDE

Propane gas is burned or pure carbon dioxide injected into the glasshouse to raise the level in the atmosphere. Sensing is by infra-red gas analysers (IRGA) and a number of manufacturers supply instruments, e.g. Seimens, Horiba, and Analytical Development Company. The relatively high cost of these instruments generally precludes an individual instrument to each glasshouse and CO₂ is therefore usually sampled by drawing air through plastic tubing to a multiplexing device from which the gas from each house can be fed sequentially through the analyser. A number of problems arise when integrating these readings into the computer system. The gas analyser is capable of analysing approximately one sample per minute; it may therefore take several minutes to sample all the houses in a complex. If the data from individual houses cannot be stored within the analyser, when the computer reads the data from the analyser an identification signal must also be present to enable the computer to relate the reading to the correct glasshouse. Alternatively, readings from individual houses may be stored in independent memories within the gas analyser or in a small peripheral computer and relayed to the main computer when interrogated.

POSITION INDICATORS

Where proportional control is required, a form of feedback mechanism is required to enable the computer to detect the position of a ventilator or valve and compare it with the desired value, as calculated from the control algorithms. To achieve this, potentiometric sending devices are attached to the ventilator or steam valve. These use additional input channels and, being electromechanical components, have a greater potential for failure than the purely electrical sensors. Alternatively, a timed pulse signal may be sent to the valve or ventilator motor; as the speed of the motor is known, this pulse can be adjusted to give the desired movement. Because this operation is carried out 'blind', variations in motor speed may result in errors and the system has to be reset periodically (e.g. hourly) by driving all motors to the closed position. While the potentiometric feedback system is perhaps the most accurate, the lack of need for additional components and lines make the timed pulse system attractive. Where a proportional controller is available, an analyser signal may be provided by the computer in which a binary number generated by the computer is converted into an analogue signal by a digital-to-analogue converter (DAC). This permits precise positional setting of valves and motors.

SOIL-LESS SYSTEMS

The development of more advanced growing systems such as nutrient film technique (NFT) and rockwool has required the additional measurements of solution conductivity, pH and temperature. Usually, the sensors are mounted in a manifold on a bypass to the main system and linked to the computer via separate conditioning electronics. Temperature and conductivity present few problems, although the conductivity may require temperature compensation. pH detection poses an electrical problem arising from the high impedance of the probe. As a result, earth loops can occur with consequent interference with the other sensors in solution. To overcome this the sensor electronics are optically isolated from the main circuitry; an example is given by Burrage and Varley (1984). Considerable damage to the crop can occur if the pH sensor fails and excess acid is added to the nutrient solution. It is general practice, therefore, to have two sensors and to cross-check readings to give greater reliability.

MEASUREMENTS OUTSIDE THE GLASSHOUSE

A weather station mounted above the glasshouse monitors incoming solar radiation, windspeed, wind direction, temperature and surface wetness. These readings are essential for the efficient operation of the system. A good example of this is the calculation of ventilator position, the factors influencing which are shown in *Figure 5.2*. A glasshouse structure is generally cooled by the operation of two

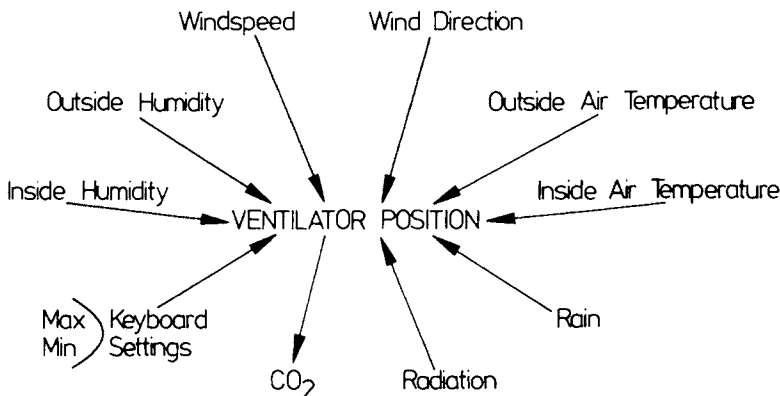


Figure 5.2 Factors influencing (inward arrows) and influenced by (outward arrow) the position of the ventilator

ventilators on opposite sides of the ridge. The leeward ventilator is usually opened to avoid possible damage caused by the wind lifting off the windward ventilator. The direction of the wind is therefore necessary in the calculation. To obtain proportional control the quantity of fresh air must be gauged, based on windspeed and temperature difference between the inside and outside of the glasshouse. For example, at windspeed $0\text{--}2\text{ m s}^{-1}$ the calculated value for opening will become the actual value, from $2\text{--}10\text{ m s}^{-1}$ the opening will be proportionally decreased, and above 10 m s^{-1} the ventilators remain closed to prevent damage to the structure.

Surface wetness readings are used for rainfall detection and result in the closure of the ventilators during rain to prevent damage to the crop. The sensor is heated to dry off surface water rapidly and to prevent the formation of frost. Solar radiation may be integrated into many areas of the control programme, e.g. light-linked temperature settings, irrigation calculations or day/night determination.

Interfacing to the computer

INPUT

The link between the computer and the outside world takes place through the interfaces. The signals from the various sensors must be presented to the computer as a digital (binary) number. The simplest form of input is the digital input which is an on or off closure that can be translated as a binary 0 or 1. This is relatively easy to make compatible with the computer circuitry. Examples of this are surface wetness and motor off/on indication. Interfacing analogue voltages from temperature and other sensors is more complex. To achieve this the voltages are processed through an ADC, the resolution of which is determined by how many binary bits it uses to represent input voltages. An 8 bit unit, which is the commonest in use, will give 256 divisions over its full voltage range. This is equivalent to a definition of $\approx 0.2^{\circ}\text{C}$ with an input range of $0\text{--}50^{\circ}\text{C}$, more than adequate for most control purposes. A 12 bit unit will give 4096 divisions, a considerable increase in definition; however, in practice this definition may be unattainable due to electrical noise picked up in the signal transmission lines. The ADC input can be multiplexed to allow a number of channels to be read. An average glasshouse unit may require six to eight inputs with a similar number of control outputs. The exact number will vary with the requirement of each individual installation.

OUTPUT

Interfacing can again be in various forms. First, the digital form where a low or high signal is presented on a single line; this is best suited to solid state switching where current requirements are low or additional electronics are available. Switch outputs are basically digital outputs, usually operating reed relays that then provide a voltage-free contact for control purposes. These usually latch until a further command is given. They provide higher current and voltage capabilities than the computer itself and isolate the computer from the remainder of the control circuitry. They may be used to drive relays or contactors that control the drive mechanisms for the ventilators or steam valves. The analogue form is used where a signal of a valve related to the opening is required, for example in proportional control ventilators. For this purpose the computer generates a binary number which is converted to analogue voltage through a DAC.

Computer

The glasshouse computer performs two major functions: firstly, to operate the control system; secondly, to provide information to the operator on the

performance of the system. Initially, the emphasis was on the development of the control algorithms to give optimum machine performance in relation to known plant response and management requirements, and developments are still continuing along these lines. The development of the information storage and retrieval facilities has been somewhat slower. However, more recently we have seen an increasing use of visual display units (VDUs) to present to the operator detailed information of present and previous environmental conditions and the performance and energy economy of the system.

It is not possible to go into detail on the programming of the computer in this chapter; one approach is given by Burrage and Varley (1984). In outline, the computer is programmed to scan the sensors at regular intervals (1 min). The data collected are compiled and converted into engineering units and compared with set values in the computer. When the actual values differ from the set values, the control operation begins by closure of relays or changing the output of the DAC. This would be after one cycle or several cycles, as determined by the software. When a motor is started the computer will monitor its movement until the correct setting is reached. If fine limits are set, the mechanical components may operate at frequent intervals. This may be disadvantageous, leading to wear and high maintenance costs. Generally, change is not initiated unless the new setting of a ventilator is 10% greater than or less than the previous setting. The computer can respond almost instantaneously to a change in environmental conditions; the hardware required to adjust to these changes may not be able to respond as quickly. For example, if a ventilator motor is moving in one direction and the computer calls for a reversal of that direction, unless the motor is given time to stop before reverse power is applied, considerable damage will occur. The computer, therefore, must be programmed to ensure that such damage does not happen, usually by giving a delay before opposing actions are taken. Band settings with upper and lower limits are more frequently used to reduce hunting, with proportional control operating within the band to maintain an even value; for example, air temperature may be set at $20 \pm 1^\circ\text{C}$ and under these conditions the heating valve would open increasingly as temperature fell below 20°C reaching a maximum extent at 19°C . In an ideal situation the valve would be opened just sufficiently to maintain a constant 20°C . Similarly, the ventilator is adjusted for temperatures above 20°C . Where a VDU is available the operation of the system and the prevailing conditions can be displayed on the screen (*Figure 5.3*) with flags to indicate the operation of valves, etc. The computer system may be programmed to operate alarms when readings deviate greatly from the preset values. These may be of various levels and may be used to check the operation of sensors. For example, to check the operation of the pH probe in an NFT system, the maximum time that the acid pump should operate in any period can be programmed into the computer. If a time greater than this is called for, a cautionary alarm can be operated to ask for the pump or probe to be checked. Similarly, the levels of liquids in tanks can be monitored and alarms sounded when they reach critical levels.

There are many variations that can be introduced into a program to suit the particular requirements of a nursery. The computer, having its own clock, can carry out timed operations, e.g. for the control of lighting, sequenced irrigation, or thermal screens which require putting over half an hour before sunset and retraction half an hour after sunrise. The computer programmed with a solar clock will perform this function throughout the year, automatically changing the timing daily. Similarly, on specific days the set temperature control times may be changed

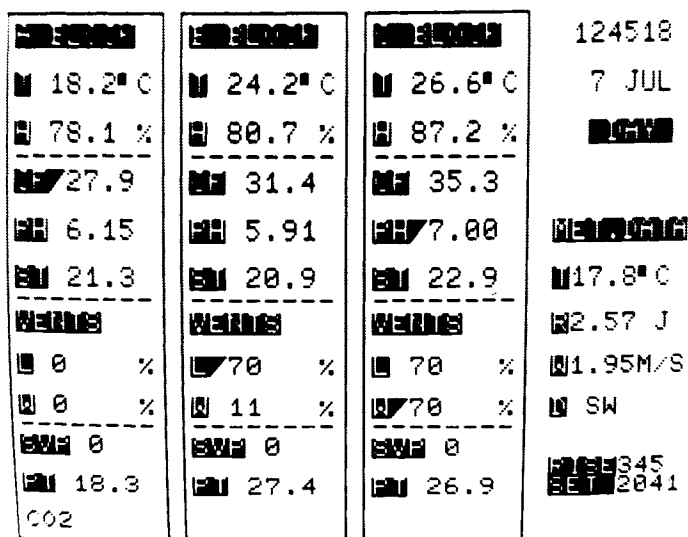


Figure 5.3 VDU display showing the previous 1 min cycle readings for three glasshouses, A, B, and C. Data from the weather station mounted above the house is indicated on the right-hand side. T = temperature; H = humidity; CF = solution conductivity (NFT system); PH = solution pH (NFT); ST = solution temperature (NFT); L = leeward ventilator opening (%); W = windward ventilator opening (%); SVP = steam valve position; PT = house pipe temperature; CO2 ON to indicate carbon dioxide application; R = incoming short-wave radiation; W = windspeed; D = wind direction. Also visible are time, date and sunrise and sunset from a solar clock. The 'flags', triangular sections, adjacent to a reading indicate computer operation of controls

to assist management. On harvesting days, for example, the higher daytime temperatures may be initiated earlier to dry off the fruit, making them easier to pick and less susceptible to damage.

Most glasshouse computer systems provide a hard-copy print-out, generally a daily analysis of data. This may be suitable where only infrequent operations are required, but where more frequent observation of information is desirable a VDU becomes essential, allowing rapid recall of data. Data can also be condensed into graphical form to make it easier for the operator to interpret. Data from the preceding 24 h may be recorded and recalled on the VDU, revealing details of the operation in the system in the absence of the grower. The ease of use of the computer is very important in building confidence in the system. It is important that the operator can communicate readily with the computer. The VDU can provide rapid feedback to keyboard operations, giving the operator a 'menu' from which he can choose his requirements. This interaction between the computer and operator must be kept simple and be responsive, e.g. changes of temperature setting must be easy to execute and easily checked.

Conclusion

The glasshouse computer control system is capable of performing more functions than its analogue predecessors. It brings levels of flexibility into control operations

that were impossible using analogue controllers. Its ability to carry out mathematical calculations has enabled the development of interactive control and its information storage capability has made it a useful tool in the wider management of the glasshouse. The performance of a system depends very much on the quality of the software and the peripheral equipment provided. The sensor technology, which also determines the accuracy and efficiency of a system, has not advanced as rapidly as that of the computer, and improvements in the areas of long-term reliability and maintenance-free sensors would be beneficial.

References

- BOT, G.P.A. and DIXHOORN, J.J. (1978). Dynamic modelling of greenhouse climate using a microcomputer. *Acta Horticulturae*, **76**, 113–120
- BURRAGE, S.W. (1981). A personal computer for glasshouse environmental control. *The Agricultural Engineer*, **36**, 35–38
- BURRAGE, S.W. and VARLEY, M.J. (1984). Microcomputers in environmental control. In *Microcomputers in Biology: A Practical Approach*, Ed. by Ireland, C.R. and Long, S.P. IRL Press, Oxford
- TAKAKURA, T. (1973). Plant growth optimization using a small computer. *Acta Horticulturae*, **46**, 147–154
- UDINK TEN CATE, A.J. and VAN DE VOOREN, J.J. (1978). Adaptive control of a glasshouse heating system. *Acta Horticulturae*, **76**, 121–125
- VAN DE VOOREN, J. (1975). A computer for crop research and climate control in glasshouses. *Acta Horticulturae*, **51**, 169–174
- WEAVING, G.S. (1980). A distributed microprocessor system for environmental control in greenhouses. *The Agricultural Engineer*, **35**, 44–46

A DISTRIBUTED COMPUTER NETWORK TO MONITOR AND CONTROL THE NIAE RESEARCH GREENHOUSES

A.W. HOOPER

National Institute of Agricultural Engineering, Silsoe, UK

Introduction

Computer control of greenhouse environments has now been an attractive commercial proposition for over 10 years. Most greenhouse computer systems are centralized, with decisions and control actions taken by a central processor. However, distributed systems, where these functions are carried out locally and the central computer used for changing set points, management and data logging, are now becoming increasingly available.

A distributed system is likely to have particular advantages in a large installation, where reduced wiring will save money and should result in reduced electrical problems with interfacing the sensors. Also, if one component of the system breaks down or is removed, the rest can continue to function (Weaving, 1981).

At the NIAE a computer system was required to monitor and control the environment in eight zones (each $6.7\text{m} \times 7.4\text{m}$) of a compartmented greenhouse used initially for comparison of cladding materials, and also in a Venlo greenhouse ($13.8\text{m} \times 29.0\text{m}$) in which it is planned to evaluate the performance of new control algorithms. When the experiments were planned, no commercially available systems offered the scope we required for data collection and storage, nor would

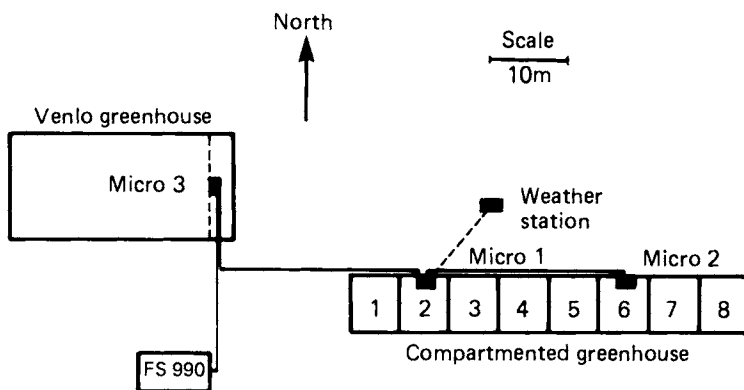


Figure 6.1 Layout of the NIAE research greenhouses

access to the software have been possible either to change control algorithms or to modify the choice of data collected. We therefore developed the system described here.

To suit these requirements a distributed computer network was developed based on Texas Instruments computers. *Figure 6.1* shows the layout of the network. Two microcomputers each control four zones of the compartmented greenhouse. They are required to maintain a similar environment in all the zones, and to collect environmental data for analysis. Micro 1 also collects data from the weather station; the weather data are then made available to the whole network. With these microcomputers it was expected that the programs could be written to a close specification, and would thus require few alterations. A third microcomputer controls the Venlo greenhouse, where it is planned to collect less detailed environmental data but where the programs are expected to require frequent modification as experiments progress.

The microcomputers

The microcomputers are Texas Instruments TM 990 series modules based on the 3 MHz, 16-bit TM 9900 microprocessor. *Figure 6.2* shows a typical microcomputer, which includes the following modules:

A single board microcomputer which includes the TM 9900 microprocessor,

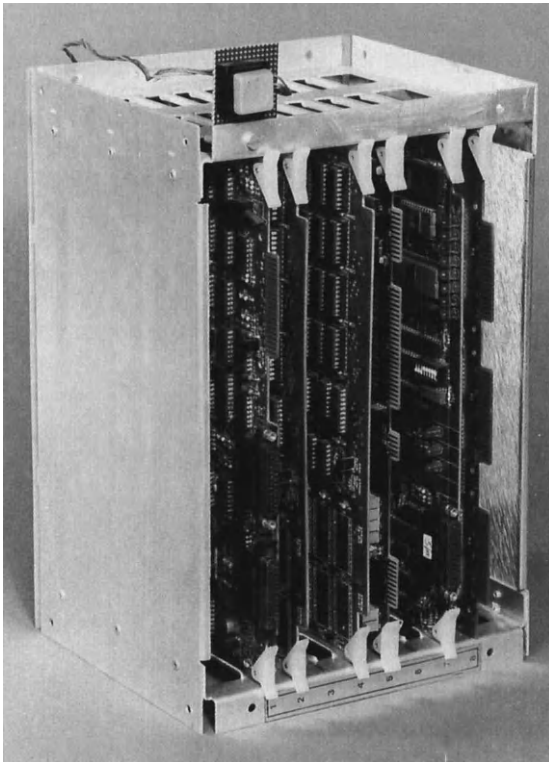


Figure 6.2 Texas Instruments TM 990 microcomputer

memory, timer and one parallel and two serial I/O ports

A memory expansion EPROM and/or RAM

A 16-channel, 12-bit analogue-to-digital converter

An industrial communications module

An industrial interface module (5MT or 6MT relay systems).

The microcomputer can address a maximum 64 kbytes of memory. Four kbytes must be allocated to the analogue-to-digital converter module, leaving 60 kbytes which can be allocated between EPROM (program memory) and RAM (data memory) in a choice of configurations.

The microcomputers are programmed in Texas Instruments Microprocessor PASCAL (MPP). This is a superset of the standard block structured high-level language. It includes all the features of standard PASCAL and also supports concurrency, interrupt handling, and single-bit input and output direct from the high-level language. An MPP source program can be written and to a large extent debugged on the central computer, and compiled into native code suitable for direct execution by the TM 9900 microprocessor. The execution speed is claimed to be 75% of the speed of optimum code written directly in assembler language. Typically, the present microcomputer programs require 20 kbytes of EPROM and 24 kbytes of RAM. There is plenty of room for expansion.

Figure 6.3 shows a microcomputer installed in a greenhouse compartment with its associated power supplies and sensor and relay interfaces.

The microcomputer selects from up to 256 individual sensors, using logic on eight lines of the parallel I/O port to address a multiplexer. A 50ms pulse on a ninth line is used to reset the integrating sensors measuring radiation or flow. At present, Micros 1 and 2 each collect data from about 110 sensors. There are 24 sensors in each compartment, plus one for steam pressure and six for the weather station. Three sensors (dew point, make-up water = transpiration rate, and carbon

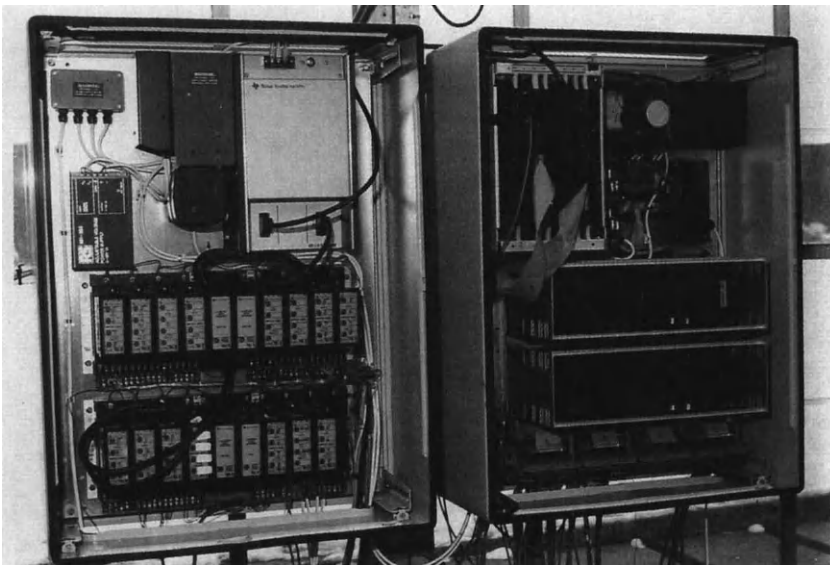


Figure 6.3 Microcomputer installation in Compartment 6 of compartmented greenhouse

dioxide), are connected to Micro 2 and are used to measure values in all compartments and outside, depending on which valves and air line are selected by the microcomputer. Each compartment is read once every 10 min in a regular cycle. The 6MT industrial relay system shown in *Figure 6.3* is used with Micros 1 and 2. A single industrial interface module can control up to 192 output relays, but no more than 60 have so far been required in the present application. The older 5MT industrial interface system is used in the Venlo greenhouse. A total of 48 outputs is available; only 15 are required at present.

The microcomputer programs are controlled by a software clock; its accuracy of a few seconds a day is governed by the on-board timer. Every minute the microcomputers measure all their sensor outputs (taking an average of three readings). Based on the measured values and the required environment, each microcomputer makes its own decisions regarding necessary control actions, and turns on the appropriate relays either for a full minute, pending a fresh decision, or for a shorter calculated time. These processes take a few seconds only. For the rest of the time the microcomputer is mainly idle, waiting for communications from the central computer.

Except where required for control action, the sensor readings are not converted to engineering units in the microcomputer. The readings (-4999 mV to $+4999$ mV) are stored for collection by the central computer which must collect them before they are overwritten 1 min later. The microcomputer program does not allow the same data to be collected twice, or data to be collected while they are being updated. The microcomputers continue to run whether the stored data are collected or not.

At present the microcomputers are programmed to control air temperature (heating and ventilation), nutrient temperature, and the pH and conductivity of the nutrient solution. The heating system is controlled by a proportional plus rate algorithm which controls the movement of valves admitting steam to a hot water calorifier in each zone. *Figure 6.4* shows an example of the temperature control

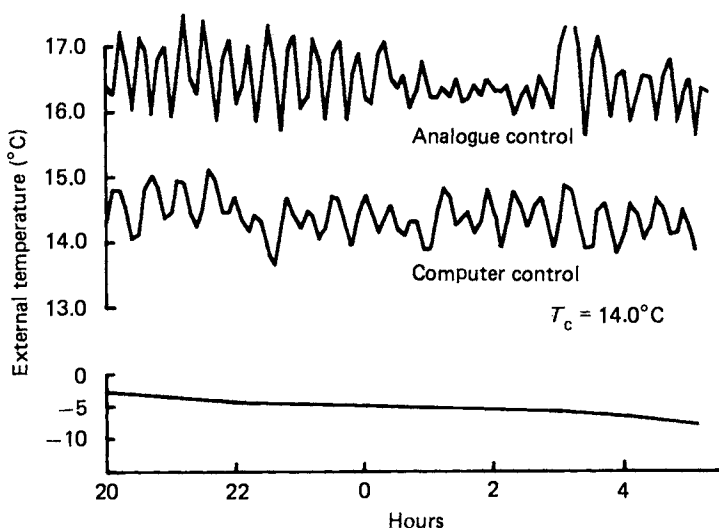


Figure 6.4 Measured temperature fluctuations in compartments with computer and analogue controllers. T_c = control temperature

achieved at present. The temperature fluctuations are $\pm 0.2^{\circ}\text{C}$, much less than those in the adjacent compartment with an analogue climate controller. Set points are used for day and night temperatures, dawn and dusk ramp times, tuning of individual compartments, control interval and valve travel times.

At present the vents are controlled by a proportional plus integral algorithm, but an adaptive algorithm has been used on some occasions (Davis, 1984). This and other adaptive algorithms will be used increasingly in the future. The algorithms allow for differential control of windward and leeward vents. The vent algorithm uses a similar range of set points to those used for the heating control. Potentiometers are used to measure the positions of the vents and heating valves. In all cases positive action is taken if the required position is 'shut'. Thus a component cannot be left open due to an error, either in the potentiometer reading or in the low limit value supplied as a set point.

The nutrient temperature control is limited to maintaining a minimum nutrient temperature using a simple on/off control.

It is planned to use the pH measurement of the nutrient solution to control the addition of 5% nitric acid, and to use the conductivity measurement to control the addition of nutrients, in particular (1) a mixture of potassium nitrate, magnesium nitrate and potassium dihydrogen phosphate, and (2) calcium nitrate. However, it has not yet been possible to test this control. Continuous nutrient flow is required to achieve the necessary mixing of the solutions. To date, the nutrient flow has been intermittent, being switched on only for several short periods each day. This is beneficial to the plants but not suitable for the planned continuous control until the tomato plants reach a certain stage of development.

The central computer

The central computer is a Texas Instruments FS 990/10. This is a 16-bit minicomputer based on the TM 9900 microprocessor, with the multi-user DX10 operating system. It has 320 kbytes of RAM memory plus four DS10 hard disks with a combined storage capacity of 20 Mbytes. The programs for this computer are written in Texas Instruments Model 990 FORTRAN, similar to FORTRAN IV. At present the installation has three VDU terminals (two with full editing capability) and one printer terminal.

The FS 990 is used for: development of MPP programs to run in the microcomputers; loading native code MPP modules into EPROM chips; development of FORTRAN programs; and data collection, analysis, display and storage.

The main FORTRAN analysis program, running on the FS 990, loads set points into whichever microcomputers are on-line, starts the microcomputers synchronously (and later maintains synchronization). As new data become available they are collected, converted to engineering units, analysed, displayed and stored. Weather data from Micro 1 are sent to other microcomputers on the network. In practice, these processes take about 20s. The program execution is then suspended until new data are available from the microcomputers.

The FS 990 can be used for more than one purpose simultaneously. New FORTRAN or PASCAL programs can be developed, and EPROMS blown, while the analysis program is running. The FS 990 has only limited graphics and display features installed. Therefore, a link (using IBM 2780 protocol) has been installed to

the NIAE's VAX 750 computer to which data can be transferred for further analysis or for (attractive) graphical display.

Communication

The communications link between the FS 990 and the microcomputers uses Texas Instruments X25/HDLC (High Level Data Link Communications) protocol. This link requires appropriate interface boards and software packages for all the computers. Communication, at 9600 baud, is via a shielded twisted pair up to 3000m long which can support up to 32 stations. Using this high-level software, all interrupt handling, error checking and, if necessary, retries are completely transparent to the user. The link is robust; no problems have been found in normal use and more than one program can use it simultaneously. Interactive programs can use the link to change set points or to inspect data at any time while the main analysis program is running.

The microcomputers act as secondary stations to the FS 990; they cannot initiate a data transfer and they cannot communicate directly with each other. Each microcomputer is activated only when it receives a message buffer (up to 128 bytes = 64 integers) from the FS 990, and it can then send a single buffer in reply. Data needed all round the network must go via the FS 990. A system of 'postcodes' and 'keys' is used to send or collect particular information to or from a particular microcomputer.

All microcomputer communication is via the HDLC link. Alternatively, the microcomputers could have been programmed to interact with a terminal using one of their serial I/O ports, but this would have required either an additional 8 kbytes of code, to utilize the otherwise unnecessary PASCAL high level read-write statements, or complicated low-level programming.

Data collection and storage

At present the following data are collected from each zone of the research greenhouse: energy consumption, steam pressure, condensate temperature and flow; use of nutrient heaters; total radiation and photosynthetically active radiation; nutrient pH and conductivity; dew point; carbon dioxide concentration; transpiration rate; and air, soil, roof, wall, leaf and nutrient temperatures. Vent positions are collected from the Venlo house (Micro 3) and weather station data from Micro 1. The appropriate sensors are read at 1-min intervals. In the case of the dew point, carbon dioxide and transpiration rate, a single sensor is used in turn for the measurements in all eight compartments and outside. The measurements for each compartment are therefore made once in a cycle which is repeated every 10 min.

Only one 5 Mbyte hard disk is available for data storage, so it is not practical to store all the data collected—this would fill the disk in about 14h. Rather, the analysis program calculates and stores averages calculated over a number of day-time and night-time periods. *Table 6.1* lists the data collected and the time periods over which averages are calculated. These averages are stored on disk, a new directory being used every day, starting at sunrise. Up to 10 days' data can be stored before the earliest data are overwritten.

Table 6.1 TIME AVERAGES CALCULATED BY ANALYSIS PROGRAM

Variable	Hourly	Sunrise to sunset	SR+2h to SS-2h	Sunset to sunrise	SS+2h to SR-2h	Sunrise to sunrise
Air (4) temperature	×	×	×	×	×	×
Moisture content	×					×
Nutrient (1) temperature	×	×		×		×
Pipe (1) temperature	×				×	×
Roof (4) temperature	×		×		×	×
Wall (2) temperature	×		×		×	×
Soil (4) temperature	×		×		×	×
Leaf (4) temperature	×		×		×	×
Radiation (Kipp and par)	×	×	×			
Ratio × Kipp/Kipp	×		×			
Ratio × par/par	×		×			
Ratio Diffuse/Kipp	×		×			
Water flow	×	×		×		×
pH and conductivity	×	×		×		×
Heat input	×	×		×	×	×
Nutrient heaters	×	×		×	×	×
U value	×				×	
Vapour pressure deficit	×		×		×	×
CO ₂	×	×				
Weather station						
Kipp, Diffuse Kipp and par	×	×				
Air temperature	×	×		×	×	×
Moisture content	×					
Windspeed	×	×		×	×	×
Wind direction	×					×
CO ₂	×	×				

sd = standard deviation

A limited selection of data is stored in more detail. All air temperature readings are stored. For four zones, one additional variable can be selected for having all readings stored and another variable can be stored graphically, either every minute or less often, in which case the running mean is graphed. At present, the vent positions are recorded only from the Venlo greenhouse but they will probably also be recorded in the compartmented greenhouse if control algorithms are evaluated there. Currently all carbon dioxide readings in the compartmented greenhouse are also stored. Using the present program, all data from Micros 1 and 2 are displayed on the VDUs and updated every minute. This is very useful for debugging or for demonstration but it does limit the computer resources available for other purposes.

Experimental results

The main experiment planned for the compartmented greenhouse is a comparison of the environment and plant performances under different energy-saving cladding materials. *Table 6.2* lists the cladding materials used on Compartments 2 to 8. Each compartment is insulated from the effects of the rest by double-glazed partition walls covered with an opaque aluminium-coated plastic sheet in between the glass.

Table 6.2 CLADDING MATERIAL USED ON EACH COMPARTMENT

<i>Compartment</i>	<i>Cladding</i>
2	Triple-walled acrylic (32 mm)
3	Double-walled acrylic (16 mm)
4	Double-walled polycarbonate (10 mm)
5	Ordinary glass (3 mm)
6	Low-emissivity glass (3 mm)
7	Double glass (6 mm)
8	Ordinary glass (3 mm)

Table 6.3 REPRESENTATIVE MICROCLIMATE MEASUREMENTS IN MARCH 1985

<i>Compartment</i>	<i>Solar irradiance</i> (W m ⁻²)	<i>Photosynthetically active radiation</i> (μE s ⁻¹ m ⁻²)	<i>Air temperature</i> (°C)	<i>Relative humidity</i> (%)
2	75	184	21.1	88
3	79	205	21.4	88
4	65	180	20.7	84
5	95	234	20.7	84
6	78	220	20.5	72
7	70	208	20.8	78
8	96	248	20.5	69
Outside	142	392	5.4	90
Outside diffuse	136			

This prevents transfer of solar radiation from one compartment to another. The compartment at the eastern end is insulated by layers of expanded polystyrene to reduce heat loss, while the west end is controlled by keeping Compartment 1 at the same temperature as the other compartments. At present Compartment 1 is not used in the experiment.

The collection, analysis and assessment of results are still at an early stage. However, *Table 6.3* shows a typical set of radiation measurements for the seven compartments and outside.

The main experiments planned for the Venlo greenhouse include evaluation of new control algorithms, initially for vent control, and later for heating and other environmental functions. It is also planned to inject CO₂ selectively into different compartments and to use the concentration measurements to estimate the leakage rates from one compartment to the next, and from each compartment to the outside. Davis (1984) has described an adaptive control algorithm for ventilation. Limited results comparing the performance of proportional plus integral, and the adaptive algorithm proposed by Davis, have been obtained in the compartmented greenhouse. *Figures 6.5 and 6.6* show that the adaptive algorithm gives satisfactory control in summer and autumn, and that the proportional plus integral algorithm, tuned to give satisfactory control in summer, gives excessive vent movement in the autumn. The self-tuning nature of the adaptive algorithm is likely to be particularly useful when applied to control of heating.

Conclusions

Although a number of measurements have yet to be made on a routine basis, Micros 1 and 2 have been responsible for maintaining the required environment

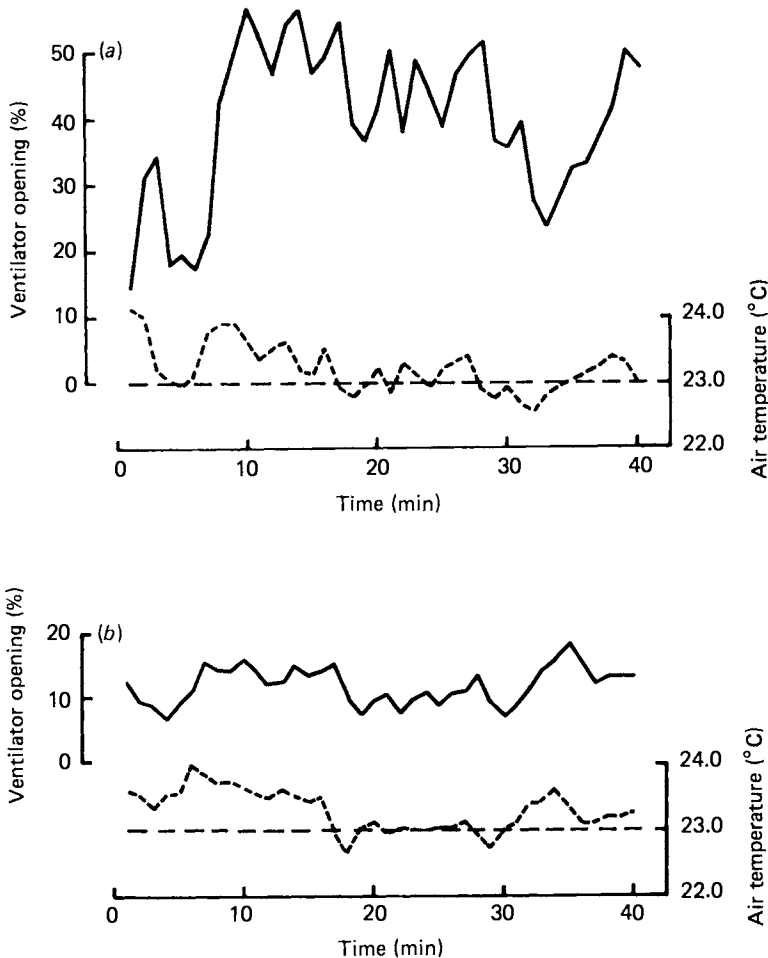


Figure 6.5 Vent movement in summer with (a) adaptive control and (b) proportional plus integral algorithms

since the tomato plants went into the compartmented greenhouse at the end of January 1985. Some tuning of the heating system remains to be done, and some sensors have yet to be fully tested. Micro 3 has been running in the Venlo greenhouse since the end of February 1985.

The network is capable of considerable expansion—allowing bigger programs, more sensors and more actuators to be used, and more microcomputers to be included in the network. Other, less sophisticated Texas Instruments control equipment (PM 550 controllers) are also compatible with the communications network. So far the equipment has proved reliable.

It is convenient that all the programs are written in high-level languages. Experience has shown that it is relatively straightforward to modify any of the programs—either the control algorithms, the data collected, or the analysis.

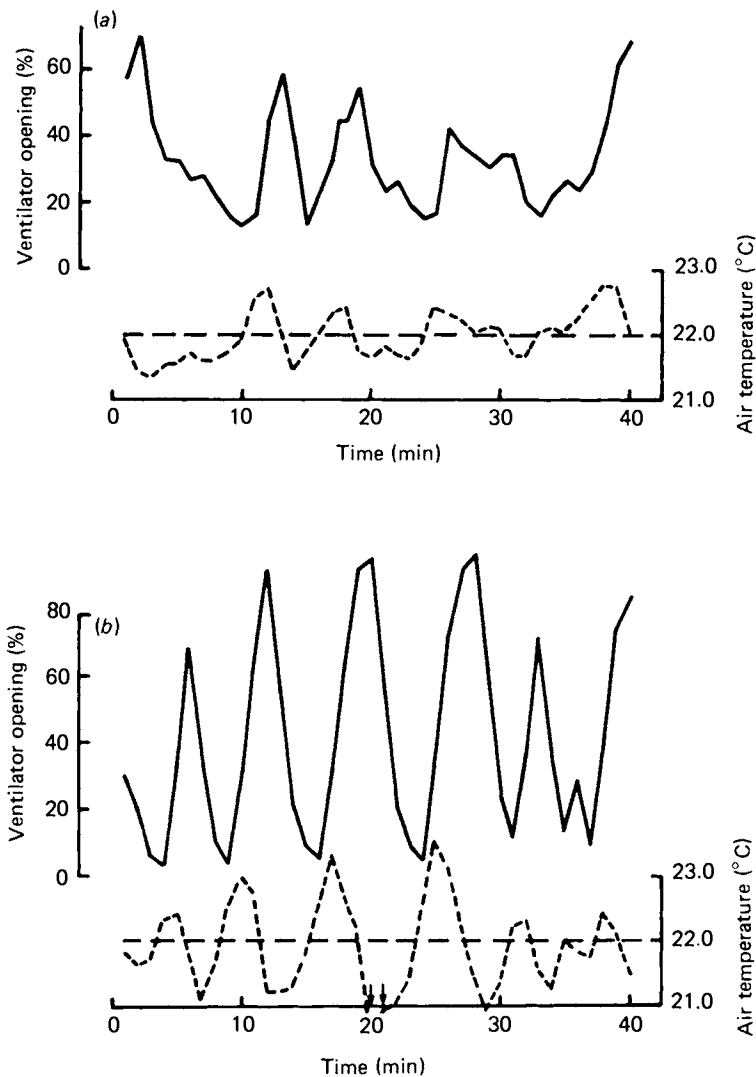


Figure 6.6 Vent movement in autumn with (a) adaptive control and (b) proportional plus integral algorithms

Acknowledgements

Many people have assisted with this project. Roger Smith and David Wilkinson of the Institute's Instrumentation Services Division designed and constructed the multiplexer and sensor interface cards. George Weaving, Bernard Bailey, Tony Lockwood and others from the Horticultural Engineering Division have been involved with the conception of the experiment, and with the installation, testing and calibration of the sensors and greenhouse equipment.

References

- DAVIS, P. (1984). A technique of adaptive control of the temperature in a greenhouse using ventilator adjustments. *Journal of Agricultural Engineering Research*, **29**, 241
- WEAVING, G.S. (1981). Monitoring and control of the greenhouse environment using distributed microprocessors. In *Report no. 35, The Fifth ARC Data Logging Symposium*. NIAE, Silsoe

DISTRIBUTED MICROPROCESSOR CONTROL FOR SIMULATED TROPICAL CLIMATES

R.A. SAFFELL and R.B. MATTHEWS
University of Nottingham, UK

Introduction

In 1976 the Overseas Development Administration initiated a research project at the University of Nottingham with a mandate to investigate the microclimatology of tropical crops. Based within the Section of Environmental Physics the project could draw on the wealth of experience gained by the Section and continue its reputation for the development of instrumentation. Previous research projects had studied the microclimatology of temperate cereals, using a computer-controlled data logger (Biscoe and Saffell, 1976). These and other measurements in natural environments have enabled much information to be obtained about the way in which plants respond to their environment. However, in order to study the effect of one environmental variable, e.g. humidity, it is necessary to grow plants in precisely controlled environments.

The rationale of the 'controlled environment' approach has been discussed by Monteith *et al.* (1983). A set of five glasshouses was built in which the temperature, humidity and carbon dioxide were controlled so that each glasshouse could maintain a different environment and therefore constitute a different experimental treatment. Originally, a 100-channel data logger controlled by a PDP 11/05 computer was used both to monitor and to control the environment by operating the heater, the ventilators and humidifier in each glasshouse. Using that system, temperature control was precise (Saffell, 1981; Saffell and Marshall, 1983), but humidity control was influenced by ambient weather conditions (Matthews and Saffell, 1986). A major disadvantage of the system was that the PDP 11/05 and data logger, which were purchased originally for the earlier project, were both quite old and less reliable than currently available equipment. It was also necessary to measure small analogue voltages with leads of up to 100m between sensor and data logger. A cable containing 40 cores was needed for each glasshouse and because the existing cable was in need of replacement it was decided to redesign the entire control system. The choice was between a system similar to that used originally but using a current minicomputer, or a distributed network of small microprocessor controllers each linked with a four-core cable to a single central microcomputer which would collate data from each glasshouse controller. The total costs were similar but for flexibility we opted for the advantages of the distributed system, using separate processors and less cabling.

Criteria

The chosen system was required to be able to measure and control temperature and humidity precisely and to scan other sensors to measure soil temperature, solar irradiance and leaf temperature in five *independent* glasshouses. A modular design offered the advantages that the operator could quickly replace any part of the system which failed with a spare component, whether computer board or sensor, and that a fault in one house would not affect the operation of the others. There are currently many computer boards available which are designed for control purposes but most are only programmable in machine language and so require skilled staff to program them. We opted to buy boards which were programmable in BASIC, thus enabling existing staff to write the software. In this application the relatively slow speed of execution of BASIC is of no consequence in comparison to the long delays associated with heating systems. We chose a system which offered readily available boards for analogue measurements and digital control outputs, all of which could be readily plugged into a common connector. The system had to be easily expandable to accommodate additional sensors. Finally, the operating program had to be stored in such a way that it could not be erased inadvertently, i.e. stored either in EPROM or in CMOS RAM with 'write protect'.

Hardware design

GLASSHOUSE CONTROLLERS

Each glasshouse was equipped with a 'glasshouse controller', housed in a weatherproof case and located near the door. A common backplane with five DIN 41612 connectors was mounted in the case to enable a total of five boards to be used. Initially, only four were required in each house (*Figure 7.1*). Of these, two were manufactured by Arcom Controls Ltd, and the other two were designed and built by our own staff; Arcom Controls have since extended their range to include commercial developments of both boards. An Arcom ARC 1 microcomputer board forms the heart of the control system. It has a 4K EPROM for storing the operating program, 4K RAM for storing data, a real-time clock, and an RS232 interface. The second Arcom board has an 8-channel analogue-to-digital converter (ADC) and a one-channel digital-to-analogue converter (DAC); both are 8-bit devices and therefore accurate to one part in 256, or approximately 0.4%. The third board is a 16-channel, 12-bit ADC board (accuracy 0.024%) which has two software selectable ranges: 0.025 V and 2.5 V, with a sensitivity of 6.1 μ V and 0.61 mV, respectively. The fourth board has eight digital outputs and is used to operate the heater, ventilators and humidifier through solid-state relays. Each channel has a

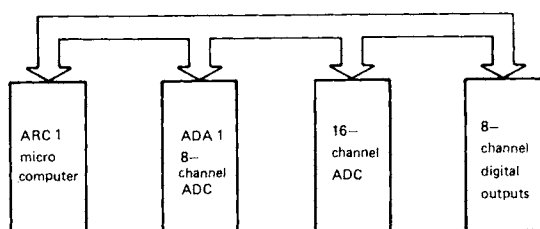


Figure 7.1 Glasshouse controller

light-emitting diode to indicate whether it is activated or not. The total cost of each glasshouse controller was under £700 (1985 prices), exclusive of the staff costs of the time taken to develop and build the system, develop the software and connect the sensors. Each glasshouse controller was connected by an independent four-core, sheathed data transmission cable to a 'Central Control'.

CENTRAL CONTROLLER

The Central Control consisted of one ARC 41 microcomputer board, and two RS232 interface boards (*Figure 7.2*). The first RS232 interface with handshaking lines enabled the ARC 41 to 'talk' to each glasshouse controller in turn. The operation of handshaking is discussed below. The second RS232 interface was purely an output device which switched four output lines. Initially, only two were used, one for a line printer for printing hourly averaged temperature and humidity

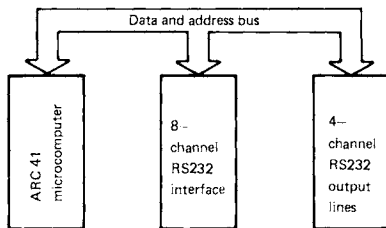


Figure 7.2 Central control

and the second to dump each day's data onto disk (through an Osborne portable microcomputer). The ARC 41 microcomputer has one 4K EPROM, 16K CMOS RAM, a real-time clock and an RS232 interface. The memory is larger than the ARC 1 boards used in the glasshouse controller due to the relatively large amount of software required by Central Control.

POWER SUPPLY

A stabilized power supply in a separate enclosure provides +24V, +12V, +5V and -12V, all at 1 A. Identical power supplies are used for each glasshouse controller and for the Central Control. A small sealed lead-acid battery maintains the 5 V supply when mains power is interrupted, thereby preventing the loss of stored data held in RAM.

GAS ANALYSIS AND WEATHER STATION CONTROLLER

It is planned to add a sixth controller to control carbon dioxide injection. The system of CO₂ control employed maintains a null balance of carbon dioxide concentration between the inside of the glasshouse and the outside, in order to simulate natural conditions in this respect. However, the rate at which carbon dioxide has to be injected to maintain the null balance can also be used to estimate the net photosynthesis of the enclosed stand. The operation and performance of the present system has been described in more detail by Saffell (1981) and Monteith *et*

al. (1983). Control involves sequentially directing air from each glasshouse to a single infra-red gas analyser (IRGA) using solenoid valves, monitoring the output of the IRGA, and controlling and monitoring the injection of carbon dioxide. The sixth controller will also be used to monitor ambient weather conditions from a weather station which is still connected to the original computer logger.

TEMPERATURE AND HUMIDITY MEASUREMENT

Measurement of temperature and humidity are made with a ventilated psychrometer mounted near the centre of each glasshouse. Saffell (1981) gives details of the psychrometer construction. The dry bulb is an integrated circuit (AD590 KH) which, when connected to a simple amplifier circuit, gives an output of 10 mV K^{-1} . Wet-bulb depression is measured as the difference in temperature between a thermocouple pair, one dry and the other wet. The output of the integrated circuit of the dry bulb is measured on the higher analogue-to-digital range, and wet-bulb depression on the μV range, resulting in measurement precision of 0.06°C and 0.15°C , respectively. However, in practice it was not possible to calibrate the dry bulb to an accuracy better than $\pm 0.1^\circ\text{C}$ (between 0 and 50°C).

Software

USE OF A MICROCOMPUTER FOR PROGRAM DEVELOPMENT

The ARC 41 board may be programmed by connecting it to a VDU terminal via the RS232 socket and typing in the program line by line in 'Tiny-BASIC'. However, editing facilities are limited and involve retyping an entire line. For the sake of convenience, therefore, a system was developed whereby the control program could be written on a microcomputer using an editor such as Wordstar and stored on floppy disk. The control program could then be transferred to CMOS RAM on the ARC 41 board or on to EPROM (via the EPIC EPROM programmer), using a transfer program written in MBASIC for the microcomputer, in our case an Osborne 1. This transfer reads the control program line by line from disk and, ignoring spaces and REM statements, sends these lines in ASCII format from the printer port to the RS232 socket on the ARC board. It was necessary to include a short delay after each line to allow the Tiny-BASIC interpreter sufficient time to process the instruction. By ignoring spaces and REM statements, the control program could be written on the microcomputer in easy-to-read format with adequate notation, while the version that was transferred to the ARC board was kept compact to conserve program space.

PROGRAM STRUCTURE

Glasshouse controllers

It was decided that the ARC 1 boards in each glasshouse would be responsible for monitoring and controlling glasshouse temperatures, humidities, and ventilator

openings, and for measuring the outputs of other sensors such as tube solarimeters and soil temperature thermometers. Measurements were to be made every minute and the hourly averages stored in RAM.

The control program for each glasshouse contains three main subroutines for the control of temperature, humidity and ventilation. The design of each of these subroutines is very similar to that given in detail in descriptions of the previous system (Monteith *et al.*, 1983; Saffell and Marshall, 1983; Matthews and Saffell, 1986). In the temperature subroutine, the dry- and wet-bulb temperatures are measured by the ADC and humidity calculated from the measured temperature using the psychrometer equation. If the temperature is too high, the heaters are turned off and the ventilators opened a little. The reverse occurs if the temperature is too low. If the humidity is too low, the humidity control routine turns on the humidifier to spray water into the house, while if humidity is too high, the humidifiers are turned off and the vents opened to remove excess water vapour by ventilation.

As there is 4K of RAM available on each board and each hour's data consists of 32 bytes, data storage for 4 days is available, allowing sufficient capacity for intermediate processing. A 'wrap around' system was used so that when the space allocated to data storage was full, new data replaced data which were 4 days old. The control program for each glasshouse was contained on a 4K EPROM with an auto-start facility, so that in the event of power failure the program would restart on power-up. After initial development, the program in the glasshouse was altered very rarely, so that an EPROM provided a convenient, semi-permanent means of storage.

Central controller

It was decided that the central controller board should be responsible only for the interrogation of each glasshouse controller, either on the intervention of the operator to change values of set parameters or, automatically, for collection of the hourly averages for output to a printer or to microcomputer floppy disk. Output to disk was designed to occur only at midnight so that the microcomputer was free for analysis of data during the day.

There is therefore a considerable degree of independence for each unit; control is entirely independent and only data collection requires central intervention. If the central controller fails, then each glasshouse controller can store up to 4 days' data before any are lost. Data can be retrieved at any time during that period if the central controller can be repaired or replaced. Similarly, if any glasshouse controller malfunctions the other units are not affected. The central controller also interrogates each glasshouse unit every 5 min to check that it is running and, if it is not, attempts to restart it. This has been found to be necessary because on rare occasions the glasshouse units stop running, possibly due to fluctuations in the mains voltage. After two unsuccessful attempts at a restart, a warning is printed.

The independence of each unit also permits glasshouse control and data storage to proceed uninterrupted during program development on the central controller. Because changes in the program in the central controller are required regularly, storage of this program on EPROM was inconvenient due to the time taken to 'burn' it in. Thus, to facilitate alterations to the Central Control program it is stored on a 16K CMOS RAM, using a back-up battery to preserve the program in the

event of power failure. Program storage occupies approximately 6K, leaving about 10K for intermediate processing of hourly and daily data from the glasshouses. Parts of the program which do not need alteration, such as tables for calculating saturation vapour pressure, are stored on a 4K EPROM on the ARC 41 board.

Integer arithmetic

The Tiny-BASIC interpreter supplied with the microprocessor supports only integer arithmetic between the values of -32768 and $+32767$, because each variable is allocated only two bytes. Calculations which would generate results outside this range would lead to erroneous results and so precautions must be taken to restrict the values used in the calculations. On the other hand, in order to maintain acceptable resolution it is necessary to use as much of the available range as possible. Thus, all calculations must be performed with these two opposing restraints in mind.

Look-up tables

The control program required some functions that are not available in the Tiny-BASIC interpreter. Temperatures are varied sinusoidally, hence the need for a sine function. Similarly, the calculation of both vapour pressure and saturation vapour pressure deficit employs a function using dry- and wet-bulb temperature measurements. The sine of a value could be calculated using series expansion, while vapour pressure could be calculated using the equation given by Campbell (1977). However, it was found that the most efficient method was to use look-up tables. Space was allocated in the top page of EPROM (locations 1F80 to 1FFF) to contain the values of the function, while the location address was used as the argument of the function.

For example, in the case of the sine function, 17 locations were used to store the sine of values between 0 and $\pi/2$ at 0.1 intervals. (The sine of 0 was stored at location 0, the sine of 0.1 at location 1, and so on.) An upper limit of 1.6 was chosen as this is the closest to $\pi/2$. In practice, to obtain maximum resolution, 200 times the value of the sine of the value was stored and the calculation was divided by 200 at a later stage. Sines of non-tabulated values were calculated by linear interpolation. This procedure introduced slight inaccuracies but these were acceptable within the limits imposed by integer arithmetic and control precision. If a value V was between $\pi/2$ and π , its sine was calculated as $\sin(\pi - V)$, while if it was between π and 2π it was calculated as $-\sin(V - \pi)$. As the maximum value of the function stored was 200 (i.e. $200 \sin(\pi/2)$) and the maximum positive value which can be stored in a single byte is 256, all the values are stored in single bytes to save space.

A similar technique was used for saturated vapour pressure, where the temperature (in increments of 1°C between the range of 5 and 51°C) was represented by the location address, and 10 times the value of the saturated vapour pressure (in mbar) was stored at the appropriate location. As the maximum value of the function was 1294 at 51°C , each value had to occupy 2 bytes. Again, linear interpolation was used for values between those tabulated. A third table stored the number of days in each month of the year, enabling the Julian day and hence day after sowing (DAS) to be calculated from the date obtained from the clock.

Handshaking

One of the main problems was to design a reliable system whereby the central controller could interrogate each glasshouse unit to send or receive data. This was done successfully by using two interrupt lines in addition to the two data transmission lines to and from each glasshouse. The operation of these is as follows.

When a particular glasshouse unit is to be interrogated the central controller program changes the status of the interrupt line to the house from low to high, and then begins to scan the other interrupt line. The glasshouse control program is designed to scan the first interrupt line frequently during its control cycle and, when it goes high, to enter a subroutine where it in turn sets the interrupt line to the central controller high, and waits for data. When the central controller detects high on the return interrupt line, it first sends an initialization sequence of three elements. The first element transmitted determines the direction in which the data are to be moved, the second determines the starting location in RAM to which they are to be sent or fetched, and the third determines the number of data elements to be transferred. The string of data elements follows this sequence. As soon as the data has been transferred, both interrupt lines return to low and the respective programs return to their normal function.

Data printout

Every hour, on the hour, Central Control interrogates each glasshouse controller and asks for a summary of the temperature and humidity during the previous hour. A typical example of an hourly print-out is shown in *Table 7.1*.

Table 7.1 SAMPLE OF HOURLY PRINTER OUTPUT FROM THE CENTRAL CONTROLLER

DAS 0	12.00 GMT	16-5-84	<i>House</i>				
			<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>
Temperature (°C)							
Desired			32.8	32.9	32.4	33.1	33.2
Dry bulb			32.2	32.6	32.7	33.3	32.6
Wet bulb			26.2	26.3	24.6	26.5	27.2
Humidity (mbar)							
Max VPD			20.0	20.0	20.0	20.0	20.0
Actual			17.9	19.3	23.9	20.9	16.6
VP			30.1	29.8	25.5	30.2	32.5
Vent position			93	13	1	13	29
Injection			2	22	54	40	2
No. scans			60	60	60	60	60

OPERATOR FACILITIES

A button inside the Central Control case interrupts the main program when depressed and calls a subroutine which connects the ARC 41 microcomputer to a

VDU terminal and asks the operator which facility he requires. Then, by inserting a code number, the operator can select one of several functions. He may ask for a display of the desired (set) temperature for each glasshouse, actual temperature, desired humidity and actual humidity, or he may wish to change one of the desired values; he can ask for a print-out of hourly averaged data for any hour over the previous 4 days; or he can synchronize the clock of each glasshouse controller with that of central control. There are a total of 12 such functions available to the operator and more can be added as the system expands.

Conclusion

Despite the need to develop three separate programs, the use of separate controllers for each glasshouse and a Central Control has been worthwhile even on this small scale. The complexity of temperature control programming has been reduced by using a hot blown-air heating system with short thermal time response and simple 'ON-OFF' control. Humidity control has, however, added to the complexity, because of the interactions with temperature control. Significant improvements could be made if the microcomputers were programmed in machine language: the memory space used would be reduced and the speed of operation increased. However, the main advantage of the system employed is that the scientists using the glasshouse facility can themselves reprogram in BASIC. In the present system, memory space is becoming limited. Without adding more memory, it would be possible to make more space available by the compromise of using machine language for the routines which are used frequently and which seldom, if ever, need to be altered, while retaining BASIC for the main program. The need for flexibility was one of the main considerations when designing the system and reflects the difference between this system and the commercial installations available at the time. At least one British manufacturer of glasshouse control systems has indicated that they can now provide this type of flexibility. Other research institutes considering this type of glasshouse facility are deciding whether to buy a complete system or to build their own. The experience gained with the Nottingham system was that it took two people a considerable time to develop but, by using the proprietary boards now available and with our experience, that time could be reduced by half.

Acknowledgements

We thank the Overseas Development Administration for support of the research programme, including a grant for the purchase of equipment described in this paper.

References

- BISCOE, P.V. and SAFFELL, R.A. (1976). A computer controlled data-logger for investigating the environmental control of the growth of winter wheat. In *Proceedings, 4th ARC Data Logging Symposium*, held at NIAE, Silsoe, Beds, pp. 1-9. Ed. by Marsh, L.

- CAMPBELL, G.S. (1977). *An Introduction to Environmental Biophysics*. Springer-Verlag, New York
- MATTHEWS, R.B. and SAFFELL, R.A. (1986). Computer control of humidity in experimental glasshouses. *Journal of Agricultural Engineering Research*, **33**, 213–221
- MONTEITH, J.L., MARSHALL, B., SAFFELL, R.A., CLARKE, D., GALLAGHER, J.N., GREGORY, P.J., ONG, C.K., SQUIRE, G.R. and TERRY, A. (1983). Environmental control of a glasshouse suite for crop physiology. *Journal of Experimental Botany*, **34**, 309–321
- SAFFELL, R.A. (1981). 'Computer control of temperature and gas exchange in experimental glasshouses.' MPhil. Thesis, University of Nottingham
- SAFFELL, R.A. and MARSHALL, B. (1983). Computer control of air temperature in a glasshouse. *Journal of Agricultural Engineering Research*, **28**, 469–477

CONTROL OF SOLAR AIR SYSTEMS IN AGRICULTURE

C.P. MEYER and R.J. FULLER
CSIRO, Griffith, NSW, Australia

Introduction

The worldwide rise in oil prices during the 1970s renewed interest in the use of the sun as an energy source. Considerable ingenuity has been applied, with some success, in attempts to use solar technology in areas ranging from domestic and industrial heating to power generation (see Duffie and Beckman, 1980). In agriculture, solar energy is particularly attractive for several reasons.

1. Major agricultural regions, especially in Australia, occur in areas of moderate temperature and high radiation. Mean daily radiation in Australia, for example, ranges from $7\text{--}21 \text{ MJ m}^{-2} \text{ day}^{-1}$ in midwinter to $21\text{--}31 \text{ MJ m}^{-2} \text{ d}^{-1}$ in midsummer (Hutchinson, 1982). The midwinter values are four to five times those recorded at Kew Gardens in the same season (Loff, Duffie and Smith, 1966).
2. Solar systems are well suited to energy-intensive enterprises operating at low to moderate temperatures. These include crop drying and space heating (Close, 1963).
3. As few rural areas are connected to natural gas supplies, the existing fuels (e.g. oil and bottled gas) are often inconvenient and expensive.
4. The rural land area required for the collection of solar energy is cheap. In addition, many farm buildings have unobstructed roofs suitable for supporting or incorporating solar collectors.

Many of the potential agricultural uses for solar energy have already been investigated, either in feasibility studies or in experimental pilot schemes. For instance, dried fruits, particularly grape products, are traditionally sun-dried on racks in the open, but the potential for drying in dehydrators is considerable (Lambert, Angus and Reid, 1980). Fleshy fruit such as bananas, which require rapid drying under controlled temperature and humidity for consistent quality, are generally dried in low-temperature dehydrators which are sometimes solar boosted (Bowery *et al.*, 1980). However, other fruits such as the current varieties of prunes require temperatures of $60\text{--}80^{\circ}\text{C}$, which are beyond the usual range of solar air systems. Some nut crops, notably peanuts and macadamias, are dried after harvest at temperatures suitable for solar boosting. Solar drying of peanuts has been considered by several groups in the USA (e.g. Troeger and Butler, 1980; Troeger, 1982).

The drying of grain has attracted particular attention (Pierce and Thompson, 1980a, b; Reid, 1980; Fraser and Muir, 1981; Sharp, 1982) presumably due to the size and value of the crop. Maize and rice are often harvested prematurely and subsequently dried artificially in order to maximize grain quality. Crops such as wheat may be harvested at water contents too high for successful storage, to avoid losses through weather damage. The potential for the use of solar energy in these applications depends largely on the drying rate required, which in turn is dependent on ambient humidity and temperature. For example, while slow, low-temperature drying is used for rice in the Riverina region in Australia, where temperatures are moderate and humidity is low, this method is inappropriate for wheat in the Darling Downs area of southern Queensland, where higher temperatures and humidity can lead to rapid spoilage of grain through pest infestation and fungal attack if drying rates are low (Reid, 1980).

Solar air systems have also been considered for kiln drying of timber (Read, Choda and Cooper, 1974). Perhaps the most complex systems in Australian agriculture, however, have been used with greenhouses (Blackwell, Shell and Garzoli, 1982; Fuller, Meyer and Sale, 1984; Garzoli, 1984; Garzoli and Shell, 1984).

Table 8.1 SOLAR AIR SYSTEMS FOR AGRICULTURAL USE IN AUSTRALIA

<i>Use</i>	<i>Collector area (m²)</i>	<i>No. of systems</i>	<i>Comments</i>
Greenhouse space heating	168	8	All use storage
Crop drying			
Bananas	504	4	No storage
Timber	56	1	Storage
Plant material	600	1	No storage

In several instances, particularly that of crop drying, the industry has adopted and developed solar technology ahead of research and extension services. Some examples of solar installations operating in Australia are listed in *Table 8.1*. Most of these, and also the majority of those reported in the literature, are controlled by basic devices such as simple or differential thermostats. While demonstrably effective, thermostats nevertheless offer little scope for optimizing system performance. Therefore, with the decreasing cost and increasing availability of microcomputers, attention should be given to improving system efficiency and reliability through more sophisticated control. This chapter discusses the dynamic behaviour of solar air systems in order to demonstrate their potential for such control.

Essentials of a solar air heating system

COMPONENTS

Solar heating systems all consist of a solar collector which absorbs radiation and then transfers the heat via a circulating fluid to either a load or storage. Both water and air systems are common, but in drying and space-heating operations the use of an air system avoids the need for a heat exchanger.

Solar air heaters are usually of the flat-plate type. Their design varies considerably, ranging from simple chambers where the air flows between the transparent cover and the absorbing surface, to collectors with complex ducting and absorber plates and consequently better performance properties (Close, 1963; Duffie and Beckman, 1980). Maximum collection efficiency ranges from 50% to near 80% (Close, 1963; Parker, 1978; Duffie and Beckman, 1980). Temperature rise through collectors, however, is limited by the decline in efficiency as operating temperature rises above ambient, and also by the need to limit power consumption of fans, and hence collector path length. Although rarely exceeding 30°C (Duffie and Beckman, 1980), this rise is quite sufficient for many heating and drying applications, certainly all those we will be discussing. Fortunately, also, the behaviour of all types of air heater is qualitatively similar, and therefore details of design can largely be ignored when designing system control.

The most common form of storage is the rockpile. This consists of beds of small rocks, usually 20–45 mm in diameter, packed between two plenum chambers in an insulated container. The rocks present a large surface area and therefore exchange heat rapidly with air that is passed over them. Although rocks do not have a particularly high specific heat when compared to water, they are usually readily available, cheap and easily handled. Rockpiles may be used with either bidirectional or unidirectional airflow.

In the bidirectional mode the rockpile is charged by passing hot air vertically downwards through it. The temperature of the air and rocks equilibrate rapidly and, with time, a temperature front also moves down through the pile. If airflow ceases, the temperature gradient remains stable. Discharging is achieved by reversing the airflow. Cold air is forced through the pile from bottom to top, being heated during its passage and driving the temperature front upwards. Heat is therefore recovered in the reverse sequence to that in which charging occurred and the amount of heat available at any time is predictable. While the behaviour of this kind of rockpile is well understood (e.g. Hughes, Klein and Close, 1976; Hollands, Sullivan and Shewen, 1984), the ducting or fans necessary to reverse the airflow make it the most complex type.

In some applications the periods of heat collection and heat demand occur at predictable times. By choosing a suitable combination of airflow rate and rockpile volume, therefore, it should be possible to arrange for the temperature front to emerge from the bottom of the rockpile at the time when heating is required (Blackwell, Shell and Garzoli, 1982; Garzoli, 1984). The need to reverse the direction of airflow in order to discharge the pile would then be eliminated, and consequently the amount of ductwork could be reduced. This mode of operation is termed unidirectional flow. Unfortunately, few studies have been made of the behaviour of such systems and hence design of reliable control strategies is difficult. Nevertheless, their apparent structural simplicity is attractive and several small systems have been incorporated into commercial greenhouses in Australia (*Table 8.1*).

CONFIGURATIONS

Solar air heaters, heat stores and conventional heaters have been combined in many configurations: four common types are shown in *Figure 8.1*. The first two configurations (*Figure 8.1a–b*) are used in drying applications where heat demand

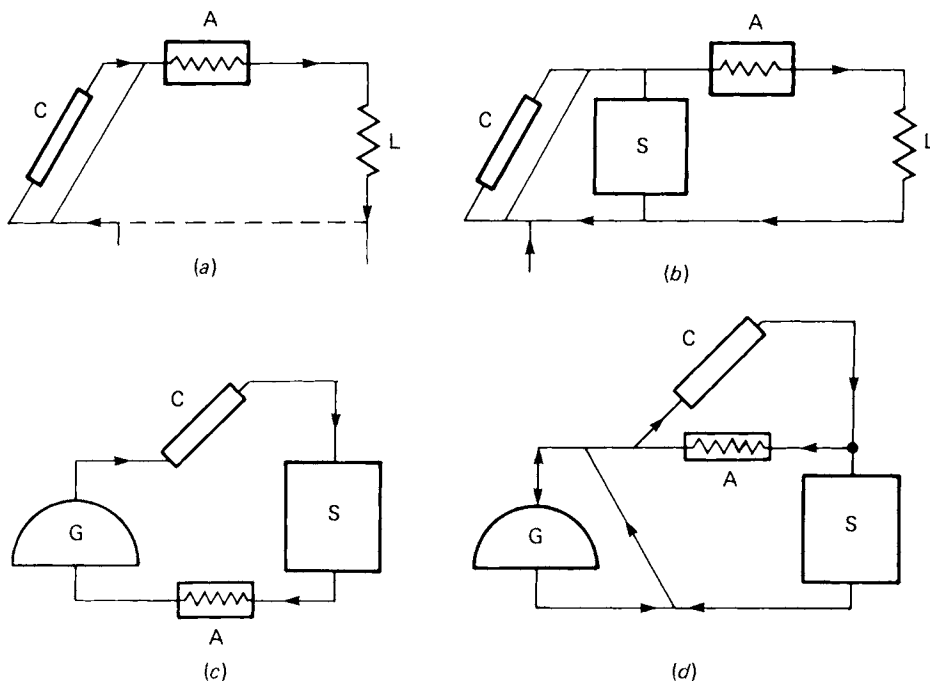


Figure 8.1 Configurations of solar air heating systems: (a) crop drier without storage; (b) crop drier with rockpile storage; (c) greenhouse with unidirectional rockpile storage; (d) greenhouse with bidirectional rockpile storage. C, collector; A, auxiliary heater; L, load; S, rockpile; G, greenhouse

is continuous, while the second two (*Figure 8.1c–d*) are suitable for night-time space heating of greenhouses.

In the simplest circuit (*Figure 8.1a*) a solar collector is used to supplement a conventional heater and no heat storage is provided. Most systems of this type are semi-closed in order to conserve heat, with outside air being introduced to control humidity. Sometimes the collector is used to preheat the ambient air (e.g. Bowery *et al.*, 1980) while in other systems the collector is incorporated into the main loop and fresh air is introduced independently upstream of it. In both cases flow through the collector is controlled by modulating dampers to divert a proportion of the air into a bypass duct.

Dependence on solar energy may be increased by increasing the capacity of the collector and storing the excess heat for use at night (*Figure 8.1b*) (e.g. Choda and Read, 1970; Troeger and Butler, 1980). Ultimately, the auxiliary heater may be dispensed with, leaving a total dependence on solar power, as in the case of the solar timber kiln (Read, Choda and Cooper, 1974).

In contrast to crop-drying systems, in solar space-heating systems heat collection and delivery are completely separate. Two configurations used at CSIRO Griffith, NSW, for greenhouse heating illustrate some of the alternatives (*Figure 8.1c–d*). The first system (*Figure 8.1c*) was a simple closed circuit incorporating the greenhouse, a solar air heater and a unidirectional rockpile. During the day, air was drawn from the greenhouse, heated further by a solar collector, then passed down through the rockpile to return to the greenhouse. At night, the collector was

bypassed to reduce heat loss, but otherwise the circuit was unaltered. Several versions of the system were built; the first were controlled by a simple thermostat (Blackwell, Shell and Garzoli, 1982), while the last incorporated variable speed fans regulated by a proportional controller (Garzoli, 1984).

The second greenhouse system (*Figure 8.1d*) (Fuller and Sale, 1983; Fuller, Meyer and Sale, 1984) was based around a bidirectional rockpile. In the main, the rockpile was charged from the solar collector in a closed loop which excluded all other devices. However, when greenhouse temperatures was sufficient the greenhouse was also incorporated into the loop, forming a circuit similar to the example above (*Figure 8.1c*). Yet another circuit was required to reverse the direction of airflow through the rockpile during heat delivery. In this case the collector was bypassed, but an auxiliary heater was included for occasions when stored heat was insufficient to meet demand. The system was controlled by a programmable logic controller, which selected the operational mode best suited to the current conditions (Fuller, Meyer and Sale, 1984). While the algorithm allowed ten modes of heating and cooling, modulation of devices was impossible: it was, in effect, an enhancement of on/off control.

Control requirements

Both greenhouses and crop driers reduce, in essence, to thermostated boxes aimed at optimizing the behaviour of the material they contain. We should consider how complex the thermostat need be.

Crop-drying specifications have usually been determined from empirical trials, which produce a single set of parameters deemed to be optimum. Predictably, this approach is changing. Peanut drying presents a good example of the way in which control specifications have evolved. Initially, drying was performed in single-pass batch driers. Control was usually achieved, at least in Australia, by rule-of-thumb methods resulting in low airflow rates ($100 \text{ l s}^{-1}\text{m}^{-3}$ peanuts), high temperatures ($40\text{--}45^\circ\text{C}$) and no humidity control. As a result, peanut quality was rather variable (McPhee, 1984). Subsequently, optimal drying conditions were specified as less than 35°C , at least 50% relative humidity and airflow rates of *c.* $200 \text{ l s}^{-1}\text{m}^{-3}$ peanuts (Blankenship and Pearson, 1976). Since air state will change during passage through the bin, these specifications are usually applied to the inlet conditions.

Most other drying applications are similarly controlled to a single set of conditions defining inlet air state. Bananas, for example, are dried at $50\text{--}60^\circ\text{C}$ and less than 50% relative humidity (Bowery *et al.*, 1980; J. Robinson, personal communication).

These approaches, though successful, fall short of what is potentially possible. Since, ultimately, we aim to control drying rate, perhaps some measure of the drying process should be incorporated into the controller. Functions relating drying rate to air state have been developed for many materials (e.g. timber and grain, Sharp, 1982) and may often be reduced to approximations describing optimal drying rate in terms of a set, rather than a single combination of humidities and temperature. Given such information, the control strategy can be broadened to select the combination best suited to the ambient air state, a technique used, for example, by Young (1984).

The interest in more precise methods of greenhouse control has also increased recently as the demand for accurate control has increased, while the cost of providing it has fallen. Some of the approaches used to achieve desired set points have been reviewed in detail by Udink ten Cate (1983 and *see Chapter 1*), and considerable interest has been shown in the possibility of adjusting set points to suit the current environment and plant response. Techniques such as controlling air temperature to achieve a specified average calculated over several days, rather than rigidly adhering to a fixed diurnal regimen, have been considered (Hurd and Graves, 1984).

These approaches raise the question of whether greenhouse systems really need to be controlled to very tight tolerances when the plants grown in them are capable of averaging out environmental fluctuations. While this is possibly true, it is nevertheless far easier to determine a control strategy and to implement it, either via a computer or manually, when there is some confidence that specified set points will be achieved in practice.

Therefore, in both drying and in greenhouse applications, the systems should be capable of maintaining with precision whatever set of conditions are specified—temperature, humidity, or air state. Conventional heating systems may be controlled sufficiently accurately to meet the most stringent specifications, albeit at some cost energetically and financially. The same may not be true for solar systems whose performance is totally dependent on the weather.

The performance of solar air systems

Solar systems are commonly assessed by average daily or monthly performance, which shows the overall effectiveness of the design. This approach is, however, of little relevance in assessing control systems in which dynamic behaviour is important. The two greenhouse systems described above (*Figure 8.1*) were monitored primarily to provide data suitable for validating mathematical models (e.g. Cooper and Fuller, 1983), but the information was also adequate for assessing system behaviour. It will be used as the basis for the following discussion.

THE BIDIRECTIONAL ROCKPILE SYSTEM

The system based on the bidirectional rockpile has the most complete data set. The greenhouse was extensively instrumented, and logged at 15min intervals or less over three operating seasons. We have selected two days in midwinter which illustrate the performance under both stable ambient conditions (July 22) and fluctuating ones (July 23, 1983).

The controller permitted ten operational modes: four for heating, two for rockpile charging, three for cooling, and one when the whole system was idle (*Table 8.2*). Normally during midwinter the system used only the two charging modes (5 and 6) and the idle mode (4) during the day, and the heating modes (0,1,2) and the idle mode (4) at night. The cooling modes (7,8,9), which were required intermittently during autumn and spring and predominated during summer, involved no solar devices (Fuller and Meyer, 1984). They will not be discussed here.

Table 8.2 MODES OF OPERATION USED BY THE BIDIRECTIONAL ROCKPILE SYSTEM

Mode	Greenhouse condition	Rockpile condition	Collector condition	Operation
0	Too cold	No heat	N.A.	Heat with auxiliary
1	Too cold	Heat available	N.A.	Heat with auxiliary and rockpile
2	Too cold	Heat available	N.A.	Heat with rockpile
3	Too cold	N.A.	Heat available	Heat with collector
4	O.K.	N.A.	No heat	Idle state
5	O.K.	Not full	Heat available	Charge pile from collector
6	Too hot	Not full	Heat available	Charge pile from collector and house
7	Too hot	N.A.	N.A.	Cool with REE and evaporative cooler
8	Too hot	Full	N.A.	Cool with REE
9	Too hot	Full	N.A.	Cool with REE and evaporative cooler

N.A. = not applicable; REE = rotary enthalpy exchanger

Daytime operation

In cool, clear days the following pattern of control was common. Rockpile charging occurred when the differential between the air temperature in the collector outlet and at the bottom of the rockpile exceeded a threshold of 7°C. Air was then drawn through the collector, down through the rockpile, to be returned again to the collector (mode 5). This condition was first reached early in the morning at a light intensity incident to the collector of $c. 400 \text{ W m}^{-2}$. As airflow commenced, however, the temperature in the collector rapidly dropped by 2°C from the static equilibrium to the dynamic equilibrium (*Figure 8.2b*). Unfortunately, the change exceeded the maximum hysteresis available on the thermostat and hence the system reverted to the idle state, to repeat the cycle (*Figure 8.2a,b*). With clear skies, radiation increased sufficiently rapidly to limit the period of hunting to about 30 min, after which a long period of rockpile charging occurred.

Soon after midday, the greenhouse temperature had increased to its upper limit (28°C) and cooling was required. Rather than waste the excess energy by ventilating the greenhouse with ambient air, it was used to supplement the solar collector and charge the rockpile (mode 6, *Figure 8.2a,b*). However, greenhouse temperature usually returned to an acceptable level within 5 min, limiting this mode of charging to a few short intervals (*Figure 8.2a*). The rate of heat collection during mode 6 was normally more than twice that in mode 5. However, taken over the day the greenhouse contribution was small (Fuller, Meyer and Sale, 1984).

During the period of charging, a temperature gradient developed in the rockpile; the top layer heated up rapidly, followed by the lower layers after an increasing delay and at a slower rate (*Figure 8.2c*). After 3 h the temperature of the rockpile bottom also began to rise, reducing the temperature differential between the rockpile and the collector outlet. Eventually the threshold was reached, causing the control to hunt between modes 4 and 5 as collector temperature fluctuated between dynamic and static equilibrium, until the static equilibrium temperature also fell below the set point.

This performance is typical of cool clear winter days, which are quite common in Griffith. Equally common are days of broken cloud when control becomes difficult. The second day illustrates system behaviour under such conditions. The morning was dull (*Figure 8.3b*), the collector outlet temperature hovered at or below the threshold (*Figure 8.3c*) and, as a consequence, the system hunted between the

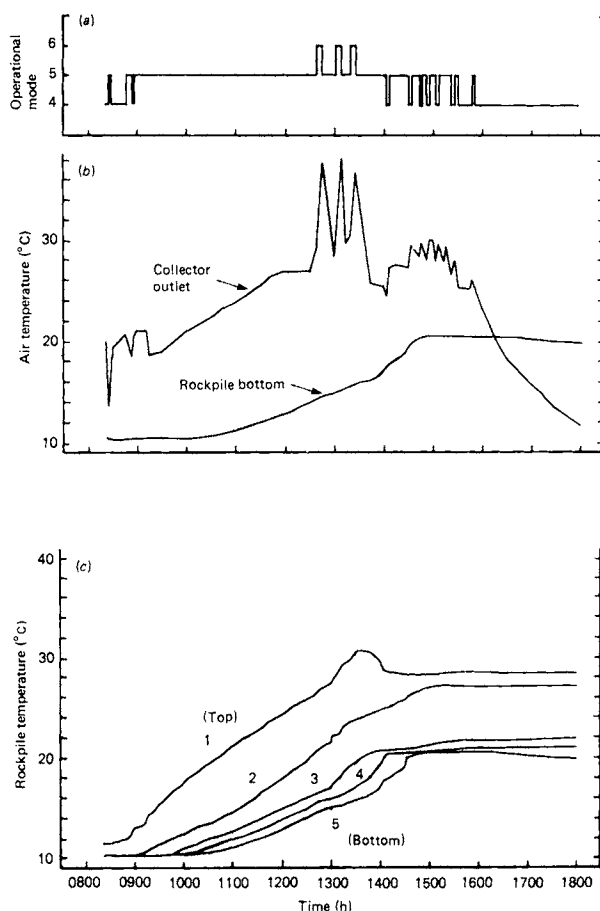


Figure 8.2 Bidirectional rockpile charging behaviour with clear sky conditions (0800–1800 h July 22, 1983): (a) operational mode; (b) collector outlet and rockpile outlet temperatures; (c) temperature changes at rockpile levels 1 (top); to 5 (bottom)

charging levels and idle states (*Figure 8.3a*). Cloud began to clear in the afternoon and radiation began to fluctuate, with collector temperature following closely, until by midafternoon both were sufficiently high for a stable period of rockpile charging. Greenhouse air temperatures had also risen to its threshold, and there were two brief periods when the greenhouse was incorporated into the charging circuit (*Figure 8.3a*).

Two important aspects of device behaviour are evident from these observations: (1) the collector responds very rapidly to changes in radiation; and (2) rockpile temperature changes very slowly, totally damping rapid changes in air temperature.

The magnitude and rate of change of collector output raises the question of whether collectors can be controlled to produce a constant output. Collector output may be defined as either air temperature or heat flux. Both may be regulated through adjustment of airflow rate as the following relations show.

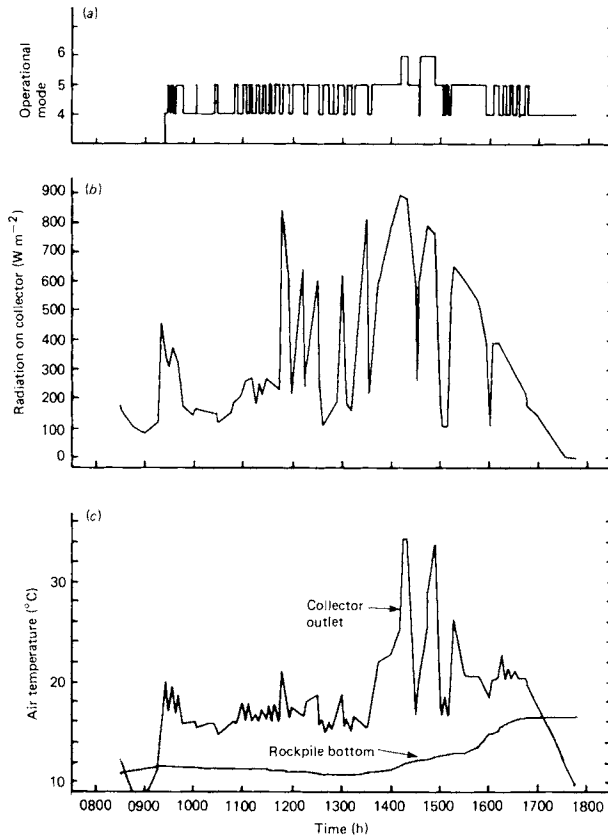


Figure 8.3 Effect of fluctuating light intensity on collector performance (0800–1800h, July 23, 1983): (a) operational mode; (b) radiation incident to collector; (c) rockpile bottom and collector outlet temperatures

The heat flux (dQ/dt) can be expressed in terms of collector efficiency (E) and incident radiation (R_n) as

$$dQ/dt = E R_n \quad (8.1)$$

where Q is the heat absorbed per unit collector area and t is time.

Alternatively, dQ/dt can be expressed in terms of the mass flow rate (m), the temperature gradient ($T_{out} - T_{in}$) and the specific heat of air (c_p):

$$dQ/dt = m (T_{out} - T_{in}) c_p \quad (8.2)$$

Combining the two equations and reorganizing gives

$$T_{out} = T_{in} + E R_n / m c_p$$

Hence, T_{out} is inversely proportional to the mass flow rate.

It should be possible, therefore, to maintain a constant outlet temperature by adjusting the mass flow rate to counteract the effects of varying radiation levels.

However, collector efficiency also varies with mass flow rate (see Parker, Colliver and Walton, 1984), increasing rapidly at low flow to approach a limit. In

most greenhouse situations the aim is to maximize heat collection; consequently, flow rates are usually chosen to produce collection efficiencies near the limit. The heat flux is then relatively insensitive to changes in mass flow.

Clearly, none of these equations includes the effects of collector capacitance. The equilibration time for air heaters varies with their heat capacity. Time constants (the time taken for outlet temperature to reach $1/e$ of the potential change) are typically near 10 min (Duffie and Beckman, 1980). Collectors of simple and light construction, such as the one used on our system, respond faster. Fortunately, the responses of control devices such as damper motors and fan speed controllers are usually faster than this. Also airflow rates are usually quite high—ours was $c.380 \text{ l s}^{-1}$ through an 11 m^2 collector—so that lag times tend to be short. The control problem, therefore, should reduce to one of changing the rapidly responding factors (airspeed and hence temperature) against a more slowly varying background of heat stored in the collector mass. This is a fairly standard problem and should be soluble.

Models describing the transient behaviour of collectors exist (Klein, Duffie and Beckman, 1974). The simpler versions are approximated by first-order equations and, therefore, it should not be difficult to incorporate them into control algorithms. To our knowledge, this has not yet been done.

The large thermal inertia in the rockpile, however, provides a far cheaper means of filtering variations in collector output. A good example of this phenomenon was shown in *Figure 8.2*, where a 10°C variation in collector outlet temperature had a small effect on rock temperature at the top of the pile, but none at the bottom. The property could prove particularly useful whenever the greenhouse is connected in series with the collector (mode 6). Greenhouse cooling is often required even in winter, as was evident on both days described above when mode 6 provided the dual functions of greenhouse cooling and rockpile heating (*Figure 8.2b and 8.3c*). In fact, if the upper set point for the greenhouse had been lower—at 24°C for example—mode 6 operation would have lasted most of the day (see *Figure 8.3*). In this situation the rockpile would have provided a stable source of cool air unaffected by transient collector behaviour.

The problem of hunting between modes 4 and 5 was more an affront to the senses of a control engineer than cause for concern of a system designer. It occurred only when the potential for heat collection was low (*Figure 8.2b,c*), and could easily have been rectified if the thermostat deadband had been larger. Of greater concern was hunting between modes 5 and 6, when the deadtime allowed for dampers to change position reduced rockpile charging time. It was caused by excessive cooling capacity and could be solved only by regulation of airflow rate.

Adjustment of flow rate in mode 6 changes the amount of heat supplied to the rockpile. However, the dilemma may not be of much significance in practice. The maximum cooling potential available from the rockpile can be calculated using *Equation 8.2*. In our system, for a greenhouse temperature of 24°C , dQ/dt was at most 6 kW. This is small compared with the radiation load on the 60 m^2 greenhouse and with the summer cooling requirements of 20–30 kW (unpublished results). Therefore, airflow rate would need to be near maximal at all times to achieve even a few degrees of cooling.

Closed-system cooling is useful when carbon dioxide enrichment is required, but has the penalty of limiting the potential for humidity control through ventilation. Since, as is commonly accepted, long-term exposure of plants to high humidity may impair growth, it may be better on occasions to sacrifice mode 6. Conventional

approaches to greenhouse environment control (Udink ten Cate, 1983) would then be applicable and the problem of collector/greenhouse interactions would be avoided.

The question still remains of whether collector output need be regulated in this system. Since the aim of rockpile charging is to maximize heat collection, which requires that the collector should always operate near its maximum efficiency, there seems little point in collector control. However, when collector outlet temperature is near the threshold for rockpile charging, some advantage might be gained by maintaining output temperature above the threshold and hence prolonging mode 5 operation.

Night-time operation

The greenhouse was heated whenever its dry-bulb temperature fell below 12°C (Figure 8.4), preferably using the rockpile store (mode 2, Table 8.2). As described

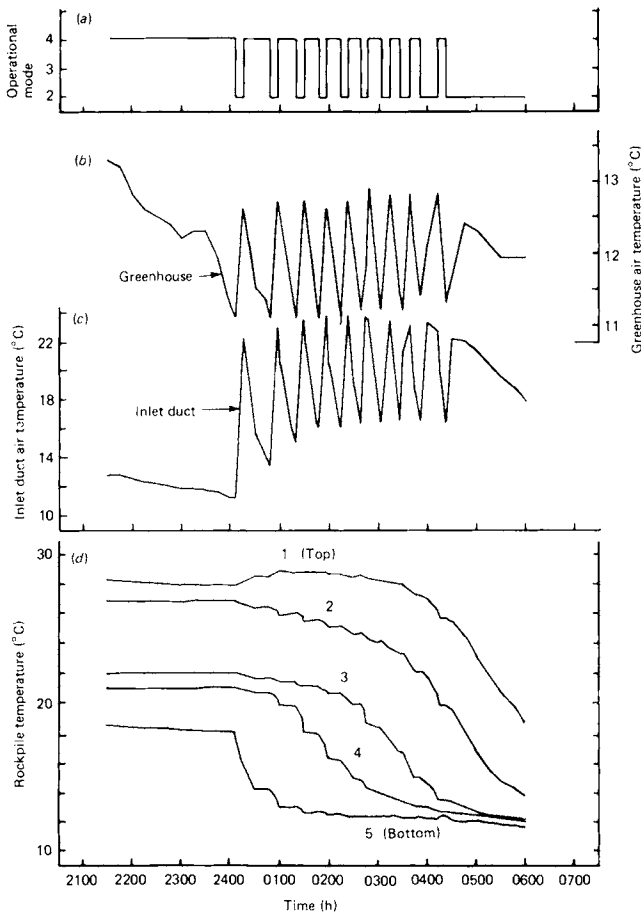


Figure 8.4 Performance of greenhouse and bidirectional rockpile during rockpile discharge (2100h, July 22 to 0600h, July 23, 1983): (a) operational mode; (b) greenhouse air temperature; (c) greenhouse inlet duct temperature; (d) rockpile temperatures at levels 1 (top) to 5 (bottom)

previously, the direction of airflow was reversed for heat delivery; cold air from the greenhouse was forced through the pile from bottom to top. The hot air was returned to the greenhouse, though with some heat loss to ductwork, then distributed from a manifold at floor level. The pattern of greenhouse temperature was typical of on/off control (*Figure 8.4b*). It was also closely correlated with inlet duct temperature (*Figure 8.4c*), demonstrating the short response times and negligible lag times typical of air systems.

The change in the rockpile temperature profile during discharging was the reverse of the charging pattern: the bottom level of the pile was depleted rapidly, with each successive layer following after an increasing delay (*Figure 8.4d*). The temperature at the top of the pile, and hence the temperature of the air returned to the greenhouse did not begin to drop until the pile was 60% empty.

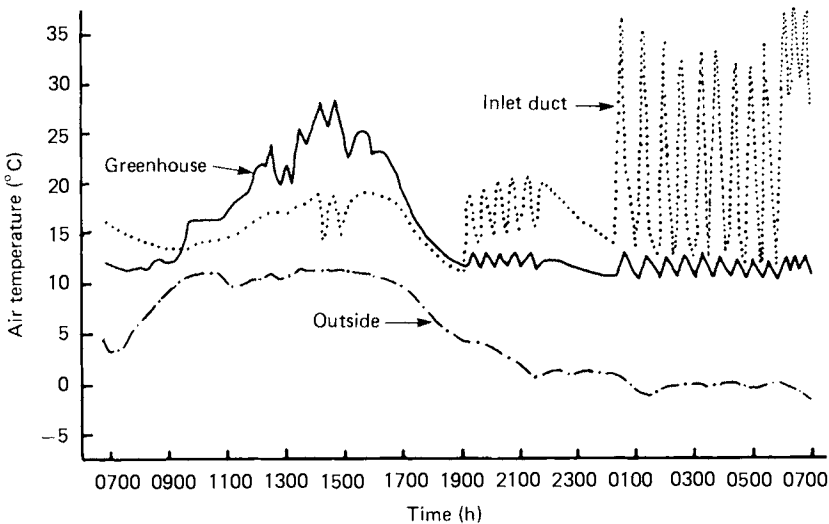


Figure 8.5 Effect of auxiliary heating on greenhouse temperature (0700 h, July 23, to 0700 h, July 24, 1983): (—) greenhouse temperature; (---) outside air temperature; (.....) greenhouse inlet duct temperature

The rockpile therefore fulfilled a prime requirement of stable control; it was a stable heat source. Although not used in our system, the rate of heat delivery could be regulated easily through flow rate. Response time was rapid, lag times could be ignored and, therefore, control should be simple.

Sometimes the rockpile store was insufficient, and the auxiliary electrical heater was used (modes 0,1). Normally the control sequence was: heat with rockpile (mode 2) until greenhouse temperature drops below 11°C, then switch on the auxiliary heater (mode 1); when the rockpile outlet temperature also drops below 12°C isolate the rockpile from the circuit (mode 0). This sequence is shown in *Figure 8.5*. The heating potential of the electrical heater (15 kW) was much higher than that of the rockpile and, consequently, the inlet duct and greenhouse temperature oscillations were also larger when the electrical heater was used. However, electrical heaters are easily controlled.

Overall, this greenhouse configuration is amenable to control because of the following.

1. Rockpile charging, the solar operation most sensitive to environmental disturbances, and rockpile discharging have no interaction. Hence control problems which might be encountered during the day do not persist, via the rockpile, into night-time operation.
2. Rockpile charging may be isolated from greenhouse temperature control, either physically or through the capacitance of the pile. Therefore, variations in collector performance have no impact on greenhouse air temperature.

The independence of rockpile charging and discharging operations is particularly important. It means that control strategies used at any given time need take no account of future heating or cooling needs. This is not the case with systems based on unidirectional rockpiles.

UNIDIRECTIONAL ROCKPILE SYSTEMS

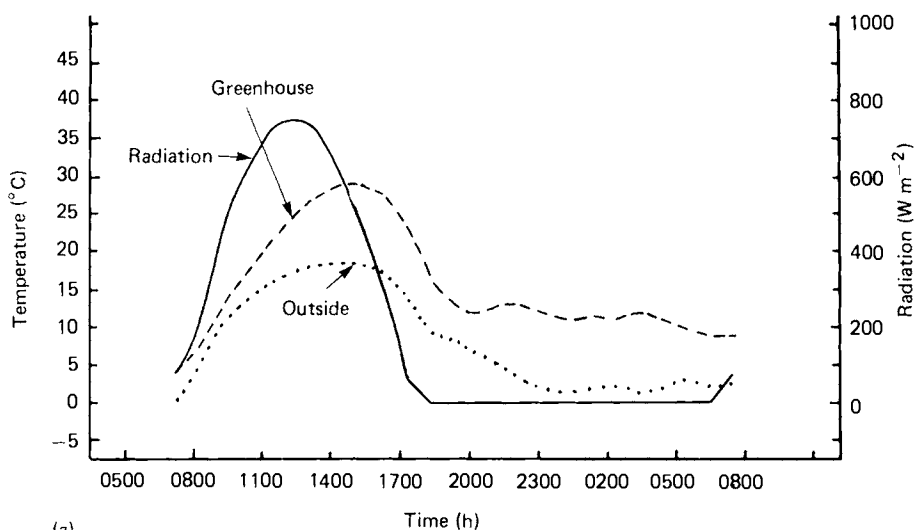
A typical day's performance for a system based on a unidirectional rockpile was published by Blackwell, Shell and Garzoli (1982). Data derived from their experiments are shown in *Figure 8.6a,b*. Greenhouse temperatures rose slowly from 5°C at 0730 to a maximum 29°C at 1530 in parallel with ambient air temperature which varied from 0 to 18.2°C over the same period (*Figure 8.6a*). Warm air drawn from the greenhouse was heated a further 5–17 degrees by the solar air collector before passing through the rockpile, cooling, and returning to the house (*Figure 8.6b*). Airflow rate and rockpile volume were chosen to ensure that the temperature front did not emerge from the bottom of the pile before nightfall. Despite this, return air temperature did rise throughout the day to 22°C by dark.

The fan was switched off between 1730 and 2030. Greenhouse air then declined slowly to the lower set point (12°C) at 2030, and a period of discharging ensued, similar to that described for the previous system. Heating was intermittent initially but increased in frequency, to be continuous by morning. The temperature of air returned to the greenhouse continued to increase, to reach 27°C at 0230 as the peak of the temperature front emerged from the pile, but decreased steadily after this to 13°C by morning.

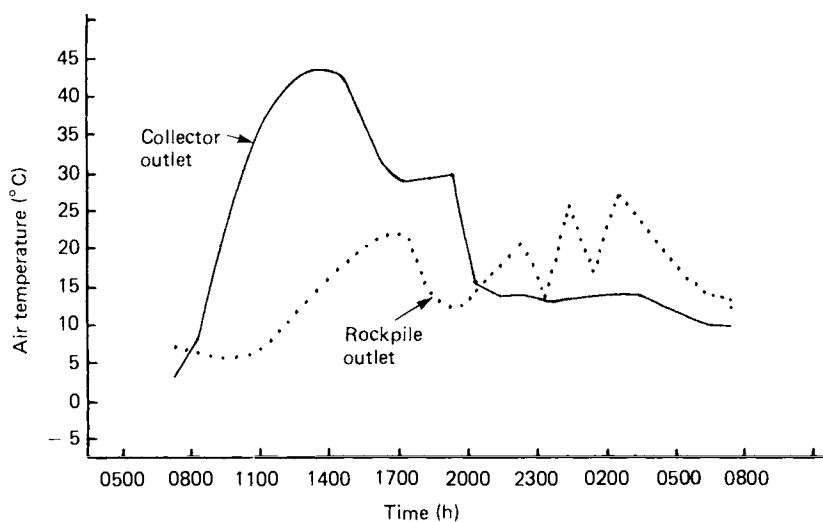
The movement of the heat pulse through the pile is shown in the rockpile temperature profile (*Figure 8.7*). Charging occurred in a manner similar to the bidirectional rockpile, but the pattern of discharge was quite different. As cold greenhouse air moved through the rockpile at night, it not only forced the front down with it, but also degraded the peak.

In this example, therefore, the system controlled greenhouse temperature within the required limits until near dawn. The thermal inertia of the rockpile slowed the rate of natural greenhouse heating in the morning, which was probably not beneficial, although overheating was certainly avoided. The heat stored was almost sufficient to meet demand and the rockpile volume was adequate for the phase shift required.

Let us consider the potential for control. In order that the heat pulse emerges at the correct time, it is important that airflow is maintained both during charging and through discharge. Regulating the rate of heat delivery by modulating flow rate interferes with this requirement. The range of adjustment available is therefore limited and affected by previous operations. For example, if it was decided to allow the greenhouse to heat more rapidly in the morning, then the flow rate through the



(a)



(b)

Figure 8.6 Diurnal changes in air temperatures in a unidirectional rockpile system. (a) (—) radiation on horizontal (W m^{-2}); (---) greenhouse air temperature ($^{\circ}\text{C}$); (.....) outside air temperature. (b) (—) collector outlet temperature ($^{\circ}\text{C}$); (.....) rockpile outlet temperature. (From data of Blackwell, Shell and Garzoli, 1982)

rockpile would need to be restricted. Heat collection by the solar air heater would also be restricted, and rockpile charging would be delayed. If heat was then required early in the night, the heat pulse in the pile might well be inaccessible. That is, the temperature at the bottom of the pile might be too low for greenhouse heating, while that at higher layers could be quite adequate. This presents a dilemma of whether to discharge cool air into a cool greenhouse in order to make

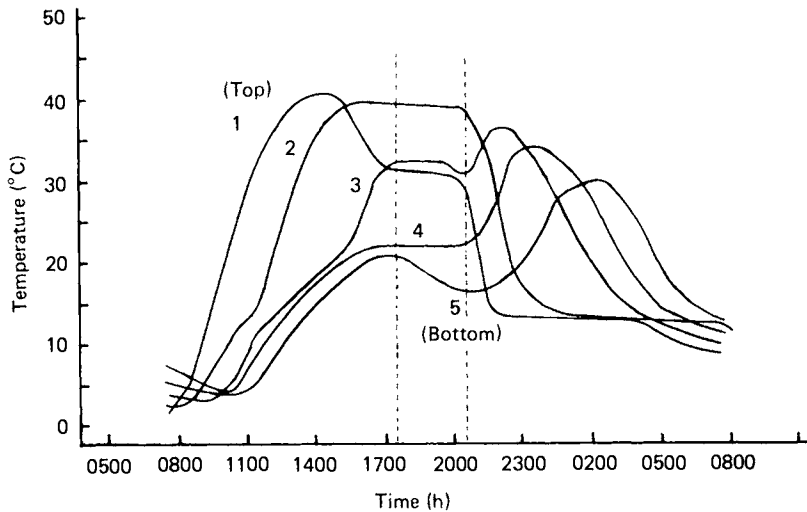


Figure 8.7 Changes in temperature within a unidirectional rockpile. Levels are numbered from 1 (top) to 5 (bottom). The main fan was switched off between 1730 and 2030, as indicated by the vertical broken lines. (From data of Blackwell, Shell and Garzoli, 1982)

the heat available later in the night, or whether to use some alternative form of heating, even though there is solar heat in the store.

In fact, this problem would have occurred in the example described *above* if the greenhouse thermostat had been set at 14°C instead of at 12°C. The greenhouse temperature fell below 14°C at 1930 (*Figure 8.6a*), when the temperature at the bottom of the rockpile was 17°C. Allowing for heat losses to the ducting, the greenhouse inlet temperature would be far less than required (*Figures 8.4 and 8.5*). Incorporating an auxiliary heater would solve the problem of greenhouse heating, but not the problem of how to regulate the rockpile.

There is also the problem of deciding where thermostat sensors should be placed. In the bidirectional system the rockpile was controlled by three parameters—the temperatures at the top and bottom of the pile and the temperature differential between collector outlet and rockpile bottom. The temperature at the top of the pile measured the actual amount of heat available for discharge at any instant, the differential set the minimum heating potential, while the bottom temperature showed the degree of charging. The amount of heat in a unidirectional rockpile can be determined only from the temperature profile. That requires at least five sensors and a considerable amount of arithmetic.

Assuming that the profile is monitored, we are still left with the problem of determining the rate at which the heat pulse should be moved and the airflow rates required. Most rockpile models are concerned only with sensible heat balances. However, in a greenhouse system latent heat exchange will also be important (Garzoli, 1984). There is considerable doubt that current models are adequate for this situation and therefore accurate predictions of rockpile behaviour for design or control might be impossible at present.

So far we have considered only the problem of providing heat at the anticipated time of demand. There is also the problem of daytime heat control and its effect on

the rate of rockpile charging. First, in order to have significant cooling potential the rockpile must be discharged by dawn; this provides a constraint on heating. Secondly, cooling requirements will vary enormously from day to day. Modulating flow rate in the manner proposed for mode 6 would restrict both the amount of heat collected and the rate at which the front moved through the pile. Night-time demands therefore place a constraint on daytime operation. Daytime temperature control in the greenhouse could, of course, be achieved without interfering with collector activity, by installing a greenhouse bypass duct and creating a mode analogue to mode 5 described above. But increasing the amount of ductwork rather defeats the purpose of using a unidirectional rockpile.

Efficient charging of the rockpile is also difficult in this system. With the bidirectional rockpile a decreasing temperature gradient could be created, by restricting heat collection to periods when radiation was significant. This option is limited with a unidirectional rockpile, again due to the need to maintain airflow.

Degradation of the heat pulse during passage through the pile might prove a problem in some circumstances, since it reduces heating potential. While 26°C inlet temperature is quite sufficient for maintaining greenhouse temperature at 10°C, it is certainly not sufficient for the minimum of 18°C required by some species. In order to achieve 26°C at heat delivery, temperatures of 45°C were required for charging (*Figure 8.6b*). Collectors of larger area or of higher efficiency than that used in the bidirectional system become essential.

These are the problems. The solutions are more difficult to find, and may always be a compromise between conflicting demands. The structural simplicity of unidirectional systems, however, appeals to the nursery industry in Australia and it therefore seems worthy of considerable effort to find some answers.

CROP-DRYING SYSTEMS

We shall now consider the other class of agricultural operations which uses solar energy—crop drying. Two system configurations were described before; one with rockpile storage, and one relying solely on the collector (*Figure 8.1a, b*). Although the former have been used in experimental situations—e.g. the solar kiln with its bidirectional rockpile (Read, Choda and Cooper, 1974) and a peanut drier (Troeger and Butler, 1980)—they seem to have little attraction for the industry. None of the commercial solar driers we have seen in Australia have used heat stores (*see Table 8.1*). One reason comes to mind. Rockpiles suitable for storing the amount of heat needed for drying are large: a 6.3 m³ solar kiln required 15.5 m³ of rock (Read, Choda and Cooper, 1974); while the peanut drier used 74 m³ of storage for 13.4 m³ of peanuts (Troeger and Butler, 1980). Justifying the space and the added complexity of these systems is difficult, particularly since auxiliary heating is still often required. Therefore, although storage systems present interesting problems for control, discussion of crop driers will be restricted to systems using only collectors.

As discussed previously, driers usually need control of both humidity and temperature. The water content of ambient air is far too low to provide the required relative humidity at drying temperature. Therefore, the most sensible solution to humidity control is to recirculate air through the drier, drawing in sufficient outside air to balance the amount of water produced by the plant material.

The required air exchange rate varies enormously with different crops. From data of Young (1984) and Troeger and Butler (1980), peanuts dry at c. $0.28 \text{ mg H}_2\text{O m}^{-3} \text{ peanuts s}^{-1}$. If their density is c. 0.25 kg m^{-3} (from McPhee, 1984), and given that temperature and humidity for the drier are 30°C and 70% (Young, 1984) and for ambient air 25°C and 63% respectively, typical for the peanut growing areas near Townsville, Queensland, an air exchange rate of $39 \ell \text{ s}^{-1} \text{ m}^{-3} \text{ peanuts}$ is required to maintain equilibrium. This is 17% of the recommended total flow through the bin (McPhee, 1984). At the other extreme, the rate for banana drying is tenfold higher (unpublished results) and the H_2O concentration in the drier is at least double, and therefore the exchange rate will be a large proportion of total flow.

As discussed previously, collector efficiency drops rapidly at very low flow rates (Parker, Colliver and Walton, 1984). Therefore, the only circuit configuration offering totally independent control of collector heat flux and air exchange rate is one in which the collector is incorporated into the main circuit, and ambient air enters upstream of it. The control strategy then becomes simple: a humidistat controls the ambient airflow rate, while a thermostat regulates the flow rate through the collector. If the humidistat operates on absolute rather than relative humidity, and therefore is independent of temperature, then the two control functions are largely independent. Ambient absolute humidity and drying rate generally change slowly, while high flow rates ensure short lag and response times. Therefore humidity control should present no difficulty (e.g. Young, 1984).

Collector performance, however, is more variable. Unlike the greenhouse systems, the output parameter to be controlled in drying applications is energy flux. As discussed *above*, energy collection can be varied by altering collector efficiency, and is usually achieved by modulating flow rate within the range where flow rate and efficiency are directly proportional. For collectors of similar design to those used on the greenhouses, flow should be less than $20 \ell \text{ s}^{-1} \text{ m}^{-2}$ collector (Parker, Colliver and Walton, 1984) which is approximately half the flow rate we actually used. Consequently, lag times will be slightly higher than in the greenhouse system. Also, unlike the situation where collector outlet temperature is regulated, collector heat capacity will vary. Nevertheless, the problem is still amenable to traditional control methods. In fact, proportional controllers designed for industrial air conditioning plants have been applied successfully to banana driers.

The addition of a solar collector to a drying system, therefore, should cause neither a reduction in the accuracy of control nor an increase in its complexity to any significant extent.

Conclusions

It is evident that the incorporation of solar devices into traditional agricultural operations need not reduce the accuracy or ease of control. However, because solar systems often require more operating modes than do conventional heating systems, the number of control devices required is usually greater. Microcomputers therefore become attractive, even when they do little more than replace a set of thermostats.

The scope for the use of microcomputers in greenhouse systems is evident. The complexity of the bidirectional rockpile system made the use of a state controller essential. Although ours performed reliably and effectively, the limitations of

on/off control remained. Accuracy could have been improved through use of a variable speed fan and proportional control.

The problems posed by the unidirectional system were beyond solution by simple control strategies and therefore are likely to be solved only by computer-based systems.

In crop drying, the scope for computers depends largely on the nature of the operation. In batch driers or automatic continuous feed driers the potential is considerable; the rate of drying can be monitored and incorporated into the control loop. Smaller operations, such as banana drying, remain labour intensive and to some degree are still adjusted by 'nose' and 'calibrated thumb'. Their requirement is for a controller to maintain a defined inlet air state.

Acknowledgements

We would like to thank Dr H. Salt and Dr T.F. Neales for their helpful criticism of the manuscript, and our many discussions. Much of the data presented in this chapter were derived from experiments run by the Protected Cropping Group, Centre for Irrigation Research, CSIRO. Many people were involved in the planning and maintenance, notably Dr P.J.M. Sale and Dr G.I. Moss, Mr R. Dalgleish, Mr G. Shell and Mr R. Speed. We thank them for their assistance.

References

- BLACKWELL, J., SHELL, G., and GARZOLI, K.G. (1982). A simple solar energy system for greenhouse heating. *Agricultural Engineering, Australia*, **11**, 9–16
- BLANKENSHIP, P. and PEARSON, J. (1976). *Effects of Airflow Rates on the Drying and Quality of Green Peanuts in Deep Beds*. Agricultural Research Service, USDA, New Orleans
- BOWERY, R.G., BUCKLE, K.A., HAMEY, I. and PAVENAYOTIN, P. (1980). Use of solar energy for banana drying. *Food Technology in Australia*, **32**, 290–291
- CHODA, A. and READ, W.R.G. (1970). The performance of a solar air heater and rockpile thermal storage system. In *Proceedings, International Solar Energy Conference, Melbourne, Australia, 1970*, pp. 147–154
- CLOSE, D.J. (1963). Solar air heaters for low and moderate temperature applications. *Solar Energy*, **7**, 117–123
- COOPER, P.I. and FULLER, R.J. (1983). A transient model of the interaction between crop, environment and greenhouse structure for predicting crop yield and energy consumption. *Journal of Agricultural Engineering Research*, **28**, 401–417
- DUFFIE, J.A. and BECKMAN, W.A. (1980). *Solar Engineering of Thermal Process*. John Wiley and Sons, New York
- FRASER, B.M. and MUIR, W.E. (1981). Airflow requirements predicted for drying grain with ambient and solar-heated air in Canada. *Transactions of the American Society of Agricultural Engineers*, **24**, 208–210
- FULLER, R.J. and MEYER, C.P. (1984). Closed system cooling of a greenhouse in an arid zone climate. *Acta Horticulturae*, **148**, 161–169
- FULLER, R.J., MEYER, C.P. and SALE, P.J.M. (1984). Energy analysis of a solar greenhouse. *Proceedings, Conference on Agricultural Engineering, Bundaberg*, pp. 168–172

- FULLER, R.J. and SALE, P.J.M. (1983). A solar heated greenhouse for maximum crop yield and low energy usage. *CSIRO Centre for Irrigation Research Information Leaflet No. 22-3*
- GARZOLI, K.G. (1984). Solar greenhouse design and performance. PhD Thesis, University of Melbourne
- GARZOLI, K.G. and SHELL, G.S.G. (1984). Performance and cost analysis of an Australian solar greenhouse. *Acta Horticulturae*, **148**, 723-729
- HOLLANDS, K.G.T., SULLIVAN, H.F. and SHEWEN, E.C. (1984). Flow uniformity in rock beds. *Solar Energy*, **32**, 343-348
- HUGHES, P.J., KLEIN, S.A. and CLOSE, D.J. (1976). Packed bed thermal storage models for solar air heating and cooling systems. *Journal of Heat Transfer*, **98**, 336-337
- HURD, R.G. and GRAVES, C.J. (1984). The influence of different temperature patterns having the same integral on the earliness and yield of tomatoes. *Acta Horticulturae*, **148**, 547-554
- HUTCHINSON, M.F. (1982). Estimating monthly mean values of daily total solar radiation for Australia. In *Proceedings, 21st Annual Conference of ISES, ANZ section*,
- KLEIN, S.A., DUFFIE, J.A. and BECKMAN, W.A. (1974). Transient considerations of flat-plate solar collectors. *Journal for Engineering Power*, **96A**, 109-113
- LAMBERT, J.M. ANGUS, D.E. and REID, P.J. (1980). *Solar Energy Applications in Agriculture*. Agricultural engineering report 48/80, University of Melbourne
- LOFF, G.O.G., DUFFIE, J.A. and SMITH, C.O. (1966). *World Distribution of Solar Radiation*. Report No. 21, College of Engineering, Solar Engineering Lab., University of Wisconsin
- MCPHEE, J.E. (1984). Influence of drying conditions on peanut quality. In *Proceedings, Conference on Agricultural Engineering, Bundaberg*, pp. 65-68
- PARKER, B.F. (1978). Performance test of three solar air heaters. *Transactions of the American Society of Agricultural Engineers*, **21**, 530-533
- PARKER, B.F., COLLIVER, D.G. and WALTON, L.R. (1984). Sensitivity of air-type solar collector efficiency to design changes. *Transactions of the American Society of Agricultural Engineers*, **27**, 915-920
- PIERCE, R.O. and THOMPSON, T.L. (1980a). Management of solar and low temperature grain drying systems—part I: Operation strategies with full bin. *Transactions of the American Society of Agricultural Engineers*, **23**, 1020-1023
- PIERCE, R.O. and THOMPSON, T.L. (1980b). Management of solar and low temperature grain drying systems—part II: Layer drying and solution to the overdrying problem. *Transactions of the American Society of Agricultural Engineers*, **23**, 1024-1027
- READ, W.R., CHODA, A. and COOPER, P.I. (1974). A solar timber kiln. *Solar Energy*, **15**, 309-316
- REID, P.J. (1980). *Solar energy applications in agriculture. III. The grain industry*. Agricultural Engineering Report No 50/80, University of Melbourne
- SHARP, J.R. (1982). A review of low temperature drying simulation models. *Journal of Agricultural Engineering Research*, **27**, 169-190
- TROEGER, J.M. (1982). Design of a solar peanut drying system. *Transactions of the American Society of Agricultural Engineers*, **25**, 763-767
- TROEGER, J.M. and BUTLER, J.L. (1980). Peanut drying with solar energy. *Transactions of the American Society of Agricultural Engineers*, **23**, 1250-1253

- UDINK TEN CATE, A.J. (1983). 'Modeling and (adaptive) control of greenhouse climates.' PhD Thesis, Landbouwhogeschool de Wageningen, Netherlands
- YOUNG, J.H. (1984). Energy conservation by partial recirculation of peanut drying air. *Transactions of the American Society of Agricultural Engineers*, **27**, 928–934

COMPUTER CONTROL OF CROP DRYING

JERRY R. LAMBERT

Clemson University, South Carolina, USA

Crop drying removes water from the harvested organ so that it can be stored and handled without spoilage or damage by mould growth, insects or mechanical fracture. We often think of crop drying as grain drying, but tobacco leaves and stems are also dried as are many other foliar materials. Forages are most often dried in the field, but are sometimes artificially dried for further processing such as pelletizing. The physical fundamentals of drying apply regardless of crop, although physiological and physical constraints may dictate variations in functional requirements. For example, drying rates and temperature of tobacco are critical to the quality of the final product. Moisture content is critical to the process of pelletizing and to the integrity of the finished product.

Environment of crop drying

A product to be dried, be it grain, tobacco or forage, has some initial moisture content and temperature which give it a characteristic water vapour pressure. When the vapour pressure of water held by the product is equal to the water vapour pressure of the surrounding air, the moisture content of the product is in equilibrium with the moisture in the surrounding air. The function of crop drying is to reduce the moisture content, generally by increasing the temperature and thus the vapour pressure difference with respect to the air.

Air is universally used as the medium to transfer water from drying products. Incoming air to the drying process may be characterized psychrometrically by dry-bulb temperature and water vapour content. Other properties such as wet-bulb temperature, dew point (or saturation) temperature, humidity ratio (mass of water per unit mass of dry air), relative humidity, specific volume and enthalpy may then be determined by use of a psychrometric chart, equations derived using perfect gas laws (with less than 1% error (Barwick, Jordan and Longhouse, 1967), or subroutines such as those developed by Bakker-Arkema, Lerew and DeBoer, (1974).

Psychrometrically, crop drying begins at state 1 of *Figure 9.1* and proceeds to state 2 by removing water from the drying product. State 1 is determined by characteristics of the incoming air, e.g. dry-bulb and wet-bulb temperatures. State 2 is determined by following the wet-bulb line from state 1 to the equilibrium curve

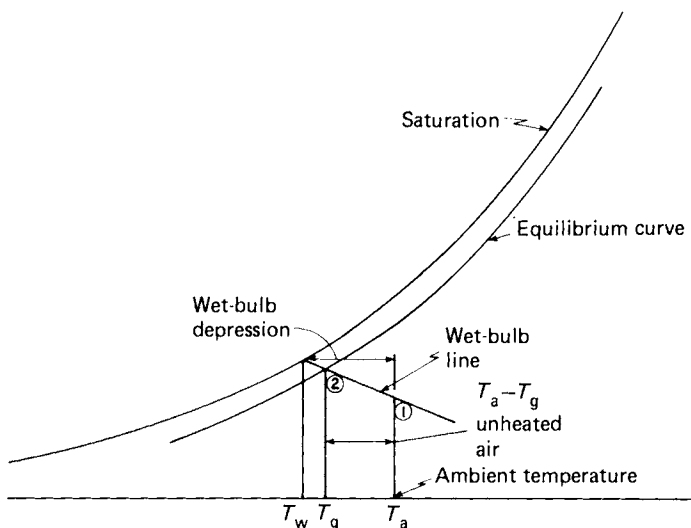


Figure 9.1 Psychrometric diagram for air changes during deep-bed drying with unheated air. 1 = state 1; 2 = state 2. (After Brooker, Bakker-Arkema and Hall, 1974)

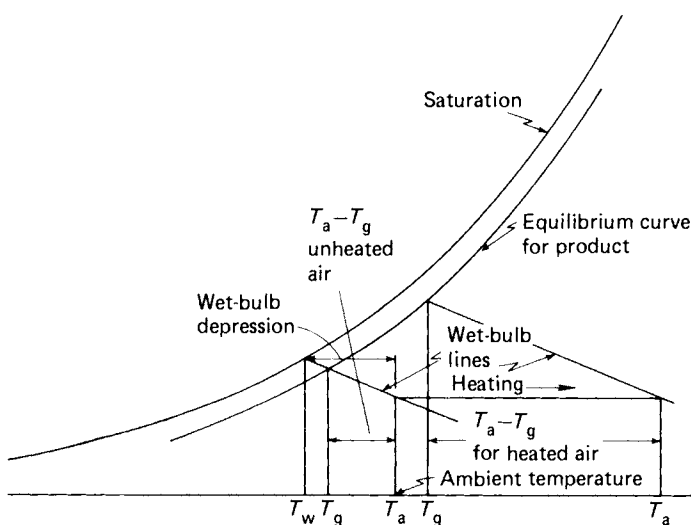


Figure 9.2 Psychrometric diagram for air changes during deep-bed drying with heated air. (After Brooker, Bakker-Arkema and Hall, 1974)

for the product being dried. State 2 assumes that air has been in contact with the product long enough to come to equilibrium. Equilibrium depends on air velocity, the psychrometric properties of the drying material and the depth of the drying material. The drying rate depends on the difference in air water vapour concentration between states 1 and 2. Heating the incoming air increases that difference and leads to higher drying rates, as indicated in *Figure 9.2*.

Optimizing drying

The functional criteria necessary for optimal drying depends on several considerations. Use of heated air costs money because of the energy requirements. Furthermore, the temperature of the incoming air must be limited, because of possible damage to the product. Grain to be used as seed should never be warmer than 40°C, while milling grain may safely reach 50–55°C. Too-high temperatures cause breakage, stress cracking, kernel discoloration and decreases in milling quality, oil recovery and protein quality. On the other hand, low air temperature and consequent low drying rates may lead to spoilage before drying can be completed. Low drying rates also dictate larger or more drying equipment to handle the required product volume.

Depth of the drying bed is interrelated with air temperature and velocity and with final moisture content distribution in the dried product. If the bed is shallow or the air velocity is high, the desired final average moisture content may be reached before the bottom layers reach equilibrium with the drying air. If the bed is deep, the bottom layers may be over-dried before the top layers have begun to dry.

Over-drying should be avoided because of additional energy requirements, possible physical damage and a very real cash loss on the market. Grain is sold by weight on the basis of a particular moisture content, with no premium for a lower moisture content. Therefore, over-drying costs energy to remove water that could be sold at grain prices.

Ideally, crop drying should remove water from the entire drying volume, down to the market moisture content, fast enough to prevent spoilage, using ambient air. Supplemental heat should be added only as economically justified to increase the drying rate. Reaching this ideal depends on the geometry of the drying system, on measuring the appropriate physical variables, on the development of algorithms to optimize the drying process, and on control of the system by operation of the algorithm.

Even after grain has been dried to a safe storage moisture content, moisture migration may cause problems. Grain is usually placed in storage bins at warmer temperatures than the subsequent air temperatures. As the bin walls cool, air and grain temperatures near the wall decrease and the air density increases. A downward flow of the heavier air along the walls, due to natural convection, along the bin bottom and upward through the centre of the warmer grain mass picks up moisture. The moist air leaves the grain mass across a relatively cold surface layer of grain which may cause water to be condensed in the upper half metre of grain at the top of the bin. Spoilage will result.

During the early spring the opposite situation may occur. Spray (personal communication) has observed moisture accumulation and consequent damage on only the north wall of grain bins in the southeastern USA.

Crop-drying systems

Typical crop-drying systems include a method to move air, typically a fan, a chamber to hold the grain or other product and, possibly, a heater to increase the temperature of the drying air. Tobacco-drying and -curing systems may use convection air movement or, more recently, forced air movement in bulk curing barns. Grain-drying systems may be divided into those that dry grain in batches and

those that dry grain as it flows continuously through the equipment. Batch drying is usually done in a bin that may also double as a storage device, usually on an individual farm. Continuous-flow dryers require additional equipment for input and removal of grain, usually in a commercial environment. The dried grain may then be stored or marketed.

Engineering ingenuity has led to a wide variety of grain-drying systems, as shown by *Figure 9.3*. Several variations of these are also offered, usually accompanied by trade names. In the simple systems grain is dried and cooled in the bin, then it may

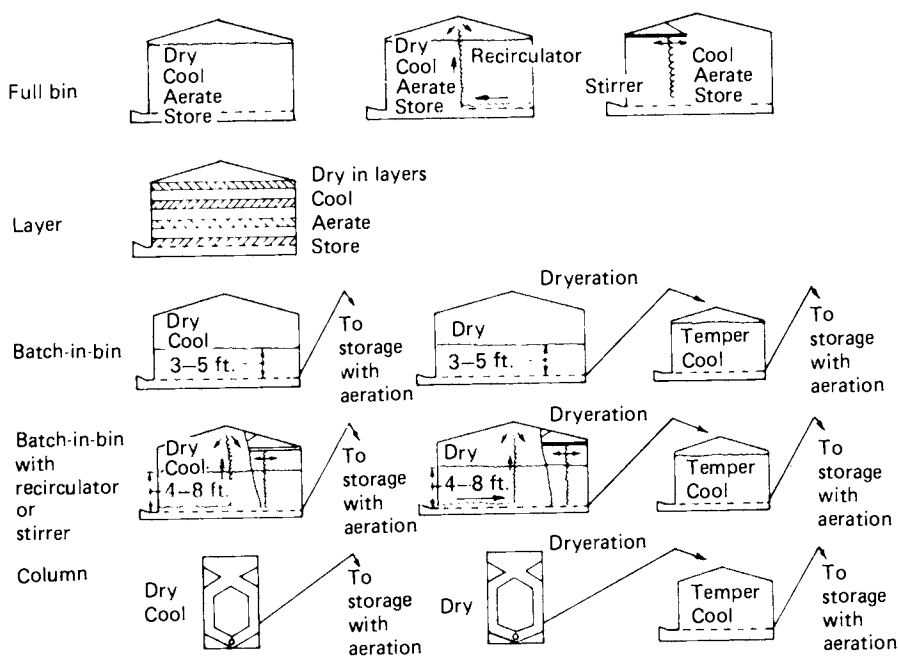


Figure 9.3 Diagrams of several batch-drying processes. (From Brooker, Bakker-Arkema and Hall, 1974)

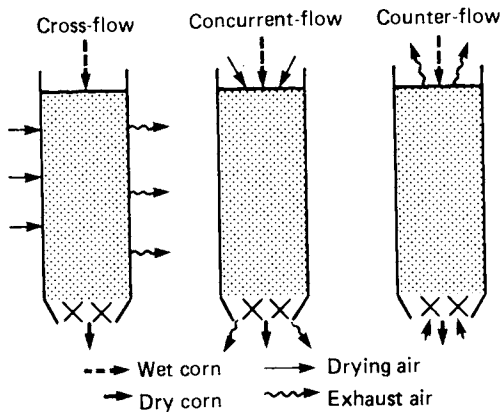


Figure 9.4 Continuous-flow drying systems, categorized by the relative directions of grain and air movement. (From Thompson, Foster and Peart, 1969)

either remain for storage or be moved to another bin or to market. In more complex batch systems the grain is dried in a bin but may be moved to another bin for cooling and on to storage or market. The capability of aeration is very desirable so that the deleterious effects of moisture migration during storage may be minimized. As indicated in *Figure 9.3*, grain-stirring or -moving devices are sometimes used during batch drying.

Continuous-flow drying systems may be categorized by the relative directions of grain and air movement through the dryer, as indicated in *Figure 9.4*: in cross-flow systems the flow of air is transverse to the flow of grain; air and grain move in the same direction in concurrent-flow dryers; in counter-flow systems air and grain flow in opposite directions.

Transducers

A transducer is a device for changing power in a system into a different form of power in a second system. Typically, engineers use transducers to change a physical variable, e.g. temperature, into an electrical or pneumatic signal. After analysis of the state of the system, deduced from the appropriate signals, a transducer may also be used to alter the state of the system, by adding heat, for example.

Variables to be measured in a crop-drying system include the temperatures of the drying air and of the product, and the humidity or other measure of water vapour. Information on air velocity is often desired, sometimes as an analogue variable and sometimes as a binary indication of flow or no flow. Knowledge of the moisture content of the drying or dried product is also desirable, preferably on a continuous, real-time basis.

Thermocouples, thermistors and resistance thermometers may be used to measure temperatures in a crop-drying system. Temperature-sensitive solid state current sources (e.g. AD590 from Analog Devices) are also excellent temperature sensors, especially in computer applications. Gas-filled bulbs and bimetallic devices are also used, particularly in mechanically controlled systems.

Humidity is often measured by a hair or other fibrous hygrometer. Adsorption hygrometers may also be used. Other recently developed electronic transducers may prove to be usable in crop-drying systems. Quite accurate dew point measurements can now be made using a thermoelectrically cooled mirror containing an embedded platinum RTD. General Eastern Instruments Corporation (50 Hunt St, Watertown, MA 02172, USA) has packaged the electronics necessary for such a device; it takes a 24 V DC input and returns a 4–20 mA signal for a dew point range of 0–50°C, for example. The mirror is about 2 mm square and encased in a probe approximately 2 cm in diameter and 7 cm long. Time response depends on air velocity as well as temperature and humidity. Dust filters and self-testing for a dirty mirror improve the potential for use in crop drying and other agricultural systems. Hygroscopic ceramic or other substrates may be used to indicate humidity of the surrounding air. The capacitance or resistance of the substrate depends on its moisture content, which depends in turn on humidity of the surrounding air when at equilibrium.

Interfacing transducers to computers

Computer control of crop drying requires a loop similar to that of *Figure 9.5*. The sensing transducer, e.g. a thermocouple, outputs an analogue signal which, *per se*,

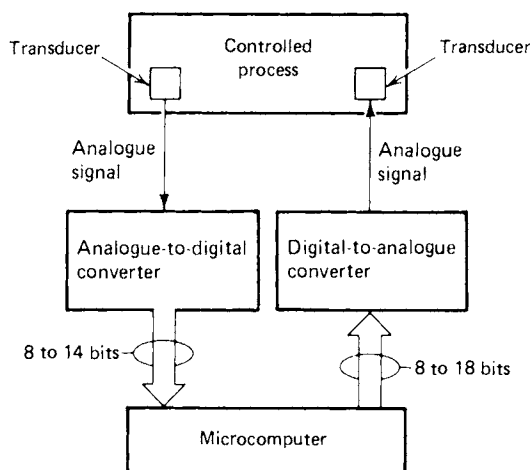


Figure 9.5 Closed-loop control of a process using a computer. (From Lambert, 1984)

is unintelligible to the digital computer. The analogue signal may require amplification or other conditioning and must be converted to digital form before it can be input to the computer. Within the computer, algorithms are coded and operate to determine the process input necessary to bring the observed variable back to the desired set point. The digital computer output variable may be converted to analogue form. A further transducer or actuator, e.g. a modulating gas valve, changes the electrical analogue signal to a mechanical form of energy in the controlled process. On/off control may be operated by individual bits output by the computer after power amplification, by a relay for example.

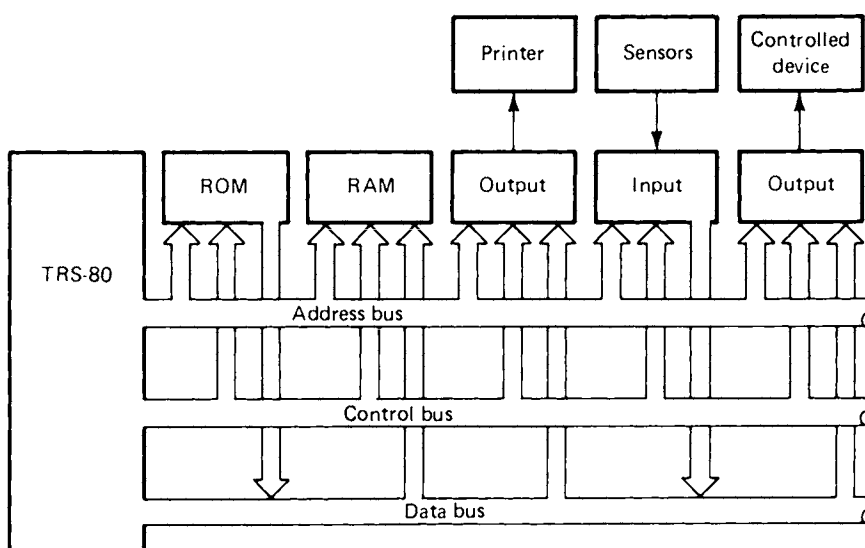


Figure 9.6 Memory and input/output devices interfaced to a computer via address, control and data buses. (From Lambert, 1984)

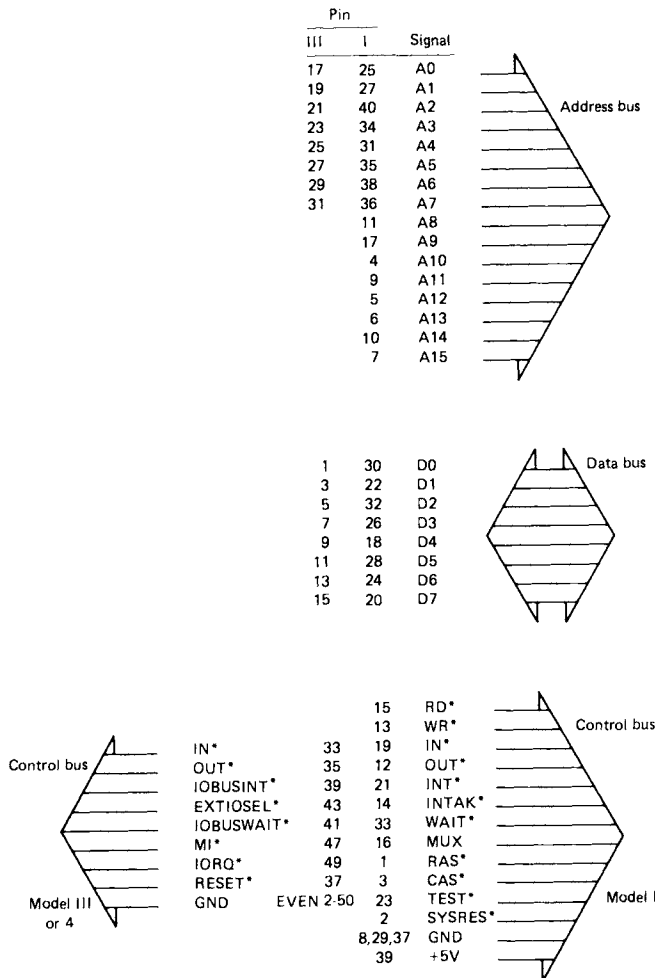


Figure 9.7 Address, data and control buses of TRS-80 computer. (From Lambert, 1984)

Signal buses are used by most small computers for transfer of information within the computer itself, between the computer and memory and between the computer and input-output devices (see Figure 9.6). They are always the focal point of all interfacing considerations.

Each signal line of a bus is always in one of two possible voltage states, high or low, +5 or 0V DC which represent the binary values 1 and 0. The data bus typically consists of eight (16 in some computers) signal lines, corresponding to the 8 bits of a data byte (Figure 9.7). The address bus consists of 16 (or more) signal lines. The address of the device selected to communicate with the central processing unit (CPU) appears, in binary, on the address bus. The control bus may consist of several signal lines. Signal logic, timing and function of the control signals are not so well defined, but vary with manufacturer of the CPU and computer. For discussion purposes I shall refer to two—the IN and OUT signals. When the

executing computer program calls for data to be input, the IN signal becomes active; when data are to be output, the OUT signal becomes active.

When data are to be input to the computer, the binary address of the selected input device appears on the address bus, the IN control signal becomes active and the CPU reads the byte of data placed on the data bus at that instant by the inputting device. The interface circuit between the computer and the device must recognize the address and IN signal combination and make the data available to the data bus, only in response to that particular request. The interface circuit must also ensure that the inputting device does not place data on the data bus at any other time. During output, the interface circuit responds to the combination of address and OUT, and captures the bit pattern on the data bus at that instant for use by the output device (see Figure 9.8).

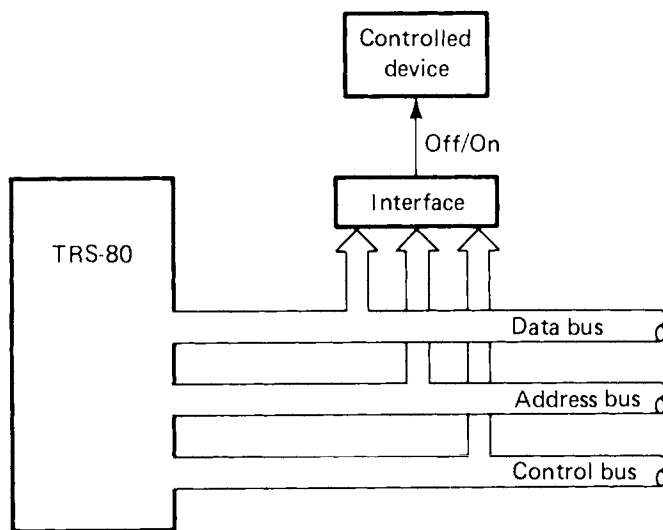


Figure 9.8 General form of the interface between the computer and any input or output device. (From Lambert, 1984)

Interfaces for specific high-volume commercial computer control applications are usually designed and constructed using individual integrated circuits and other components (Lambert, 1984). For prototype or low-volume production systems, interfacing boards are available for many of the more common computers. Use of such products eases the task of interfacing transducers to the controlling computer. For example, third-party vendors market an expanding array of interface boards for the IBM PC, including the following: 16 channels of 0–1 to 0–10 V DC 12-bit analogue input; 2 channels of 0–5 to –10–+10 V DC 12-bit analogue output; 24 bits of digital input/output; 16 channels of thermocouple signal conditioning; and assorted combinations of the above on one board. One such vendor is MetraByte Corporation (254 Tosca Drive, Stoughton, MA 02072, USA); one of its combination boards has 16 single-ended analogue input channels, two channels of analogue output, four digital input channels, four digital output channels, a 3-channel programmable interval timer and software for linearization, calibration, graphics and set-up.

Computer control systems

A computer-based system for control of crop drying includes several components. Sensing transducers must supply information about the physical variables of the system. Signal conditioning and interfacing circuitry make the data compatible with requirements of the digital computer. The computer itself must be programmed to read the necessary input data, to perform the desired control algorithms and to write the output data. Interfacing and output signal conditioning transform the computer output into a form appropriate to the controlling actuators.

Commercial systems

A few research-oriented computer-based control systems are being used in laboratories, as will be discussed *below*. At present, two commercial systems for control of grain aeration and drying are available in the USA. Neither offers the versatility and power of a fully instrumented and computerized system, but nor do they carry the price tags.

Performance Technology Corporation (P.O. Box 289, Trimont, MN 56176, USA) markets a controller intended for in-bin aeration and low-temperature drying. The 6805-based device uses up to six thermistor grain-temperature sensors, an air-temperature sensor and a film-based humidity sensor to provide on/off control of up to five fans and a heater. Two programs are available for providing aeration or low-temperature drying, dependent on ambient temperature and humidity, time and grain temperatures. An RS-422 port is available for digital communication. The controller has a 32K memory.

Sentry Technologies, Inc. (P.O. Box 498, Excelsior, MN 55331, USA) has shipped over 1000 Sentry Pacs, at a price of near US \$1500 each, for aeration of stored grain. The user provides three inputs to the preloaded program: grain type (e.g. wheat), desired moisture content of stored grain, and desired hours per day of aeration. A thermistor senses ambient temperatures and a Panasonic ceramic sensor provides humidity information to a 8031-based preprogrammed controller with 8K RAM. An optional grain probe provides the temperature near the top of the bin. The software is designed to provide aeration when ambient conditions are equivalent to the previous 3-week average temperature and the user-input desired moisture content is within an initially narrow band of moisture content which is widened if ambient conditions do not permit the cumulative desired aeration time. Because the Sentry Pac provides only near-optimum aeration for cooling, some farmers believe that the rule of thumb of 120h at $0.11 \text{ m}^3 \text{ min}^{-1} \text{ tonne}^{-1}$ (0.1 cfm/bushel) airflow to get a 5.5°C (10°F) temperature change can be halved.

Research

Bunn, Dunlap and Hammond (1983) used a microcomputer to control drying of corn, wheat and soybeans. The software was based on equilibrium moisture content equations and utilized a psychrometric chart program to match ambient drying potential to expected grain moisture contents. The computer controlled the drier heater to assure a minimum drying rate relative to a preselected final grain moisture content. Warnock and Wafler (1982) built and tested a cross-flow grain

dryer test unit using a microprocessor to monitor dry-bulb and dew point temperatures and to control the partial pressure of water in the drying air for four drying chambers by injecting steam.

Information in the CRIS research data base indicates that McLendon (Georgia) has evaluated an algorithm and computer hardware for low-temperature grain drying using initial and final grain moisture content, allowable drying time, and ambient dry-bulb and dew point temperatures to calculate, hourly, the lowest allowable drying temperature that will yield an acceptable drying rate. Results indicate that energy requirements can be reduced by 14% when the optimum drying temperature is maintained. Several other researchers in the USA are researching dryer design and management strategies with the goal of reducing drying energy requirements, usually by reducing drying temperature, while maintaining grain quality. Among them are Bakker-Arkema (Michigan), Brooker (Missouri), Morey (Minnesota), Kline (Iowa), Thompson (Nebraska), Olver and Shove (Illinois) and Foster (Purdue).

Summary

The water vapour pressure differential between a product and the drying air causes product drying. Heated air speeds the process but is less energy efficient and may lower product quality. Aeration during storage is often necessary to reduce the deleterious effects of moisture migration. To optimize drying and aeration rates and efficiency, as influenced by grain and weather conditions, requires transducers to measure grain and air temperatures, humidity and, preferably, grain moisture content. Interfacing circuitry between input and output transducers and the controlling computer makes the different electrical requirements compatible. Computer software implements the desired algorithm to control fans, heaters, conveyors, dampers and stirrers such that system performance is optimized. Researchers are using such computer-based control systems and a few commercial controllers are being used, especially for aeration control.

References

- BAKKER-ARKEMA, F.W., LEREW, L.E. and DEBOER, S.F. (1974). 'Grain dryer simulation.' Research Bulletin, Agricultural Experiment Station, Michigan State University
- BARWICK J.A., JORDAN, K.A. and LONGHOUSE, A.D. (1967). Accuracy of computer evaluation of moist air properties. *Transactions of the American Society of Agricultural Engineers*, **10**, 579–583
- BROOKER, D.B., BAKKER-ARKEMA, F.W. and HALL, C.W. (1974). *Drying Cereal Grains*. AVI Publishing Co., Westport
- BUNN, J.M., DUNLAP, J.L. JR and HAMMOND, R.G. (1983). Energy efficient drying through computer control. In *Proceedings of the ASAE Symposium, Energy Management and Membrane Technology in Food and Dairy Processing*
- HALL, C.W. (1957). *Drying Farm Crops*. AVI Publishing Co., Westport
- LAMBERT, J.R. (1984). *Interfacing to the TRS-80 Computer*. Reston Publishing Co., Reston

- THOMPSON, T.L., FOSTER, G.H. and PEART, R.M. (1969). Comparison of concurrent-flow, crossflow and counterflow grain drying methods. *USDA Marketing Research Report*, No. 841
- WARNOCK, W.K. and WAFLE, P.D. (1982). 'Microprocessor control of a crossflow grain dryer test unit.' ASAE Paper No. 82-3009

COMPUTER SIMULATION AND CONTROL OF GRAIN DRYING

M.E. NELLIST, R.D. WHITFIELD and J.A. MARCHANT
National Institute of Agricultural Engineering, Silsoe, Beds, UK

Introduction

The application of the digital computer to the artificial drying of grain is one of the success stories of agricultural engineering. Most agricultural environments are a complex combination of many variables, the majority of which are likely to be uncontrollable. Whilst this is true of the natural drying of grain in the ear, it is not so true of the 'artificial' drying of grain after threshing, where such factors as air temperature, humidity and flow, and bulk properties of the grain, if not entirely controllable, may often be either measurable or relatively constant. Thus, a decade or so before digital computers became widely available to drying engineers, the essential physics of the artificial drying process had been worked out from small-scale laboratory experiments. However, although much insight was gained, it was not possible to apply such theory directly to commercial-scale drying, mainly because the required volume of calculation was prohibitive. Although Van Arsdel (1955) had perceived that the drying of a deep bed of grain could be described by the numerical integration of a set of heat and moisture transfer equations and M'Ewen and O'Callaghan (1954) had suggested a simplified graphical solution, this was not simple and quick enough to be of much use in practice. So it was that by the early 1960s drying research had reached something of an *impasse*. The breakthrough, in which the integration was done by digital computer, came first in two papers by Boyce (1965, 1966), followed by papers by Bakker-Arkema, Bickert and Morey (1967) and by Thompson, Peart and Foster (1968). Since then the models have been improved and built into computer programs, simulating almost every possible agricultural drying situation, and have been used to study many aspects of design and operation.

Although the main preoccupation has been with the thermodynamic processes, it should be noted that the aerodynamic processes governing the airflow in ducts and crop bulks have also been modelled (see, for example, Nellist, 1979). In the future there is likely to be increasing emphasis on combined analyses of thermodynamic and aerodynamic processes so as to model the behaviour of driers in which air and grain flows are highly non-linear.

Thus, the computer simulation of grain drying provides an excellent example of the use of the digital computer in an agricultural application. The aim of this chapter is to illustrate this by summarizing the development and use of the mainly thermodynamic models and to discuss their application to drier control.

Modelling the drying process**DRYING IN THIN OR EXPOSED LAYERS**

Analysis of the drying process begins with an understanding of the mechanism of the loss of moisture from the individual grain. It has long been known that the loss of moisture from a wet body into a drier atmosphere is analogous to the loss of heat from a hot body and follows an exponential law of decay. In the simple case when all the resistance to drying resides in the grain surface then, by analogy with heat transfer, we can express the drying rate by Newton's equation:

$$\frac{dM}{dt} = -k(M - M_e) \quad (10.1)$$

where M = moisture content (decimal dry basis; m.c.d.b.), M_e = moisture content at equilibrium, k = drying constant (s^{-1}) and t = time (s).

Unfortunately, it is relatively easy to show experimentally that this is a poor description of the drying rate, but it is not easy to substitute improved equations which have general application and acceptance. Thus, in practice, *Equation 10.1* is still very widely used, while research into what is commonly called 'the thin-layer drying rate' of grain has continued more or less unabated over 30 years.

The integral of *Equation 10.1*

$$M = (M_0 - M_e) \exp.(-kt) + M_e \quad (10.2)$$

can be rewritten as

$$MR = \exp.(-kt) \quad (10.3)$$

where M_0 = moisture content at time zero and $MR = (M - M_e)/(M_0 - M_e)$ and is termed the moisture ratio.

Equation 10.2 is a particular solution of Fick's Law of Diffusion for a body in which all the resistance to diffusion is concentrated in the surface. In more realistic solutions, which take account of the internal diffusion of moisture through the grain, the single exponential term becomes replaced by an exponential series. These solutions account for the initially higher rate of drying obtaining while a moisture gradient is established across the grain but do not allow for the reduction in diffusivity (and hence the value of k) with decreasing moisture content. Numerical solutions, in which the grain can be considered to be divided into a number of concentric shells, can be used but become expensive in computer time. However, there are situations, e.g. tempering between drying, where their use is necessary. The comprehensive model of Fortes, Okos and Barrett (1981) takes into account both heat transfer and the transfer of moisture in liquid and vapour phases. So far, it has not been used in deep-layer calculations.

Several empirical modifications of *Equation 10.2* have been suggested. Of these, the equation of Page (1949)

$$Mr = \exp.(-kt^n) \quad (10.4)$$

is both effective and relatively simple. For maize, the equation of Thompson, Peart and Foster (1968)

$$t = a \ln MR + b(\ln MR)^2 \quad (10.5)$$

where a and b are coefficients, is commonly used.

All these equations describe the drying of a single grain or, more realistically, a thin layer of representative grains exposed to air at a single temperature and humidity. Drying in this way occurs only in the laboratory under controlled conditions. In the far more complex environment of a farm or commercial-scale drier, the grain experiences a continuing change in temperature of the air and moisture with which it is surrounded and its 'drying curve' no longer approximates to any of *Equations 10.2–10.5*.

The differentials with respect to time of *Equations 10.2–10.5*, such as *Equation 10.1*, can, however, provide an estimate of the drying rate to be expected at any point and at any instant in a grain bed, and this estimate can be used to solve, i.e. numerically integrate, equations of the heat and moisture transfer which will occur in a thick bed of grain subjected to through ventilation with air.

HEAT AND MOISTURE TRANSFER EQUATIONS

The equations are developed by considering the changes in the temperature and moisture content of the grain within, and in the temperature and humidity of air passing through, a thin layer during a short time interval. Including *Equation 10.1* and, written in finite difference notation, the four equations applied at NIAE (Nellist, 1974) to model drying with heated air are:

$$M = -k(M - M_e)\Delta t/(1 + \frac{1}{2}k\Delta t) \quad (10.6)$$

$$\Delta T_g = \frac{A + \rho \frac{\Delta M}{\Delta t} \left[\frac{2Y}{hS} + \frac{\Delta z F}{GE} \right]}{\left\{ 1 + \frac{\rho}{\Delta t} \left[\frac{2B}{hS} + \frac{\Delta z}{GE} (B + C_{pl}\Delta M) \right] \right\}} \quad (10.7)$$

$$T_a = \frac{-\rho \Delta z}{GE\Delta t} (\Delta T_g(B + C_{pl}\Delta M) - \Delta MF) \quad (10.8)$$

$$H = \rho \frac{\Delta z}{G} \frac{\Delta M}{\Delta t} \quad (10.9)$$

where T_g = grain temperature ($^{\circ}\text{C}$); T_a = air temperature ($^{\circ}\text{C}$); ρ = density (kg m^{-3}); hS = volumetric heat transfer coefficient ($\text{kJ s}^{-1} \text{m}^{-3} \text{K}^{-1}$); z = depth of bed (m); G = mass rate of flow ($\text{kg s}^{-1} \text{m}^{-2}$); C_{pl} , C_{pv} , C_{pg} , C_{pa} = specific heat capacities of water liquid, water vapour, grain and air at constant pressure ($\text{kJ kg}^{-1} \text{K}^{-1}$); H = absolute humidity of air ($\text{kg water/kg dry air}$); L_a , L_g = latent heat of vaporization of water at 0°C and in seed (kJ kg^{-1}); $A = 2(T_a - T_g)$; $B = (C_{pg} + C_{pl}M)$; $E = [C_{pa} + C_{pv}(H - \rho \Delta z/G \Delta M/\Delta t)]$; $F = (C_{pv}T_a + L_a - C_{pl}T_g)$; and $Y = (L_g + C_{pv}T_a - C_{pl}T_g)$.

The equations are solved by simple Euler integration. Although this method is economical in computing time, it provides no check on the integration error. However, comparison with the more rigorously formulated and solved equations of Parry (1983) and with results (Pierce and Thompson, 1981) from the semi-empirical model of Thompson, Peart and Foster (1968) has shown that, provided the description of grain properties is the same, the models give similar results.

Equations 10.6–10.9 can be used to model the drying with unheated or slightly heated air typical of bulk-storage driers, but for most low-temperature applications

they can be simplified (see Sharp, 1982). Parry (1984) has reviewed the development of the heat and mass transfer equations of drying and explained the common features of what, at first sight, appear to be different approaches.

In the NIAE model for heated-air drying, the solution assumes that the grain bed in a drier can be divided into a number of thin layers and that the changes occurring in the layers in a small time interval, Δt , can be calculated successively in the direction of airflow. The model can be set up for the three types of parallel-flow drier, viz. cross-flow, concurrent-flow, and counter-flow, and can approximate the non-linear case of the 'mixed-flow' or 'cascade' drier by assuming that this type approximates to a succession of concurrent-flow and counter-flow beds (Bruce, 1984). Although providing excellent overall results (Miller and Whitfield, 1984), the prediction of detail is less satisfactory and is the subject of continuing research at NIAE.

PREDICTING GRAIN QUALITY

An important feature of the NIAE model is the calculation of probable changes in the germination of the grain. Work is in progress to incorporate similar algorithms for calculating changes in other quality criteria, e.g. baking quality of wheat.

The model (Nellist, 1981) for calculating the loss of grain viability is based upon the 'probit' hypothesis of seed ageing developed by Roberts (1960) and his colleagues at Reading (Ellis and Roberts, 1980, 1981). In long-term studies of seeds stored in conditions of constant moisture and temperatures, it was found that although the time scale varied with conditions, the *pattern* of seed deaths was always the same. At first, the rate of death would be so low that changes in viability were difficult to detect. Gradually, more seeds would begin to die and the death rate would accelerate to a maximum, at which time half the seeds would have died. Thereafter it would necessarily decline to a very low level. Thus, the sigmoid shape of the death curves reflected the normal distribution of the seed deaths in time and could be represented by the integral of the normal distribution. Replacing the probability, P , by the decimal value, G , of the germination, we can write:

$$G = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{X = \frac{\bar{t} - t}{\sigma}} \exp.(-\frac{1}{2}X^2) dX \quad (10.10)$$

where X = standardized normal deviate, $\bar{t}$ = time at $X = 0$, and σ = standard deviation or inverse death rate.

Equation 10.10 can be used to transform values of G into equivalent values of the abscissa, X , which when plotted against t give straight lines of the form

$$X = X_0 - t/\sigma \quad (10.11)$$

where X_0 = value of X at time zero. The abscissa, X , is known as the standardized normal deviate and is the basis of the scaling of 'probability' paper. Ellis and Roberts (1980) coined the term 'probit viability' to describe the values of X when used to describe viability. In Equation 10.11, the rate of death, $1/\sigma$ (the inverse of the standard deviation), is constant for all values of t and X and losses of 'probit viability' are additive. Furthermore, a most important finding of Ellis and Roberts

(1980) was that the value of σ in a given environment was not affected by the previous history or initial quality of the seed. Thus, probit values can be used in a manner analogous to logarithms—a loss of probit viability can be accumulated and the value of X_0 adjusted. Then the resulting value of X can be transformed back to a normal viability value, G . This is the procedure used to calculate the loss of viability in a grain drier; the total loss is the sum of the losses at each combination of grain temperature and moisture content calculated for each short time interval. The procedure works but, because the physical model underpredicts the initial rise in grain temperature, the present version tends to underpredict damage at temperatures above 65°C . We are confident that work in progress will correct this deficiency.

VALIDATION AND APPLICATION

Computer simulation of drying is valuable because drying experiments are time-consuming, expensive and subject to uncontrolled variations. This also means, however, that drying models are not easily validated; data are either few or inadequate. Nevertheless, most authors have carried out some validation of their models and, even though it is not easy to set up precise criteria by which to judge the results, it can be said that, in the main, agreement between computed and

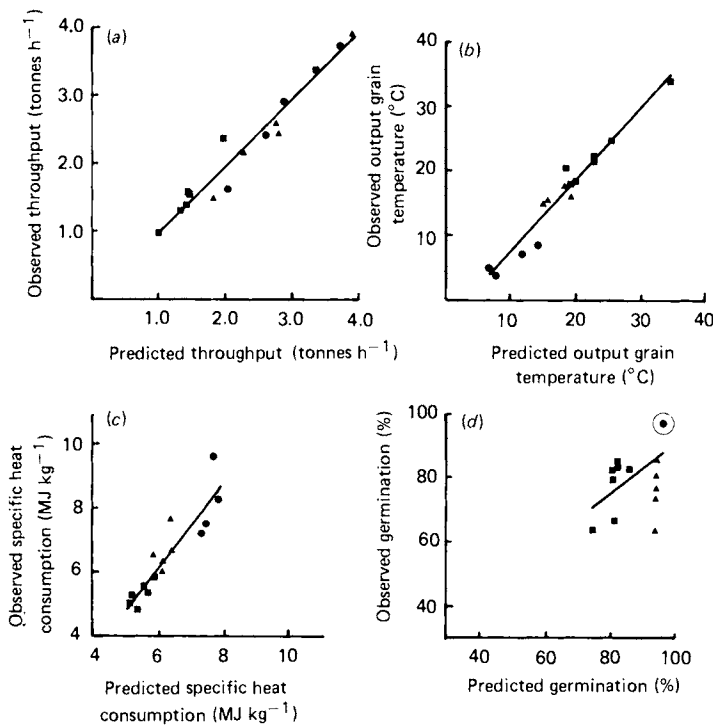


Figure 10.1 Comparison of observed *versus* computer-predicted values of throughput (a), output grain temperature (b), specific heat consumption (c), and germination (d) for Airwoods (■), Gascoigne (●) and Allmet (▲) cross-flow driers. (Note: these particular driers are no longer manufactured)

experimental results is good. By way of illustration, a recent study (Nellist, 1986) compared the observed steady state performances of three cross-flow driers tested by the NIAE between 1962 and 1964 with performances predicted by the NIAE cross-flow drier simulation. Regression relations between observed and predicted throughput, specific heat consumption, output grain temperature and germination are plotted in *Figure 10.1* and the coefficients of the regression are given in *Table 10.1*. For the three physical parameters of performance agreement is excellent, but prediction of germination is less good. In this case the discrepancies are not only due to deficiencies in the biological model discussed *above* but also to large variations in the observed data. However, the physical results provide a very reliable base from which to illustrate two applications of the model.

Table 10.1 COEFFICIENTS OF LINEAR REGRESSION BETWEEN OBSERVED (y) AND PREDICTED (x) PARAMETERS OF PERFORMANCE OF THREE CROSS-FLOW DRIERS (NELLIST, 1986)

Quantity	Intercept	Slope	Correlation coefficient
Throughput (tonnes h^{-1})	-0.012	0.982	0.98
Specific heat consumption (MJ kg^{-1})	-2.14	1.39	0.91
Output grain temperature ($^{\circ}\text{C}$)	-3.46	1.11	0.98
Germination (%)	12.7	0.78	0.52

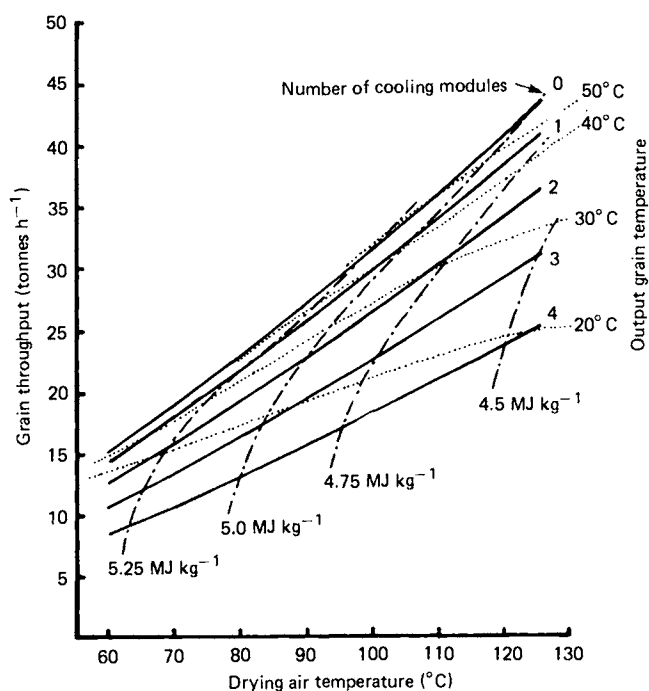


Figure 10.2 Computed effect of drying air temperature on the grain throughput of an eight-module, mixed-flow drier when drying from 20% to 15% moisture content (w.b.) and using from zero to four modules for cooling. Lines of equal specific heat consumption (---) and equal output temperature (.....) are also shown

First, *Figure 10.1* shows that all three driers have a similar range of throughputs but that their specific heat consumptions tend to be different. Compare, for example, the plots for the Airwoods (■) and Gascoigne (●) models. The Airwoods appears to have a lower specific heat consumption than the Gascoigne, but is this attributable to a difference of design or to conditions at testing? Certainly there was a difference of 12°C in the mean ambient temperature at testing. However, by simulating the driers at one standard air condition and moisture removal, it was possible to show that there was a genuine difference due to design. This facility to correct test results to defined operating conditions is now a regular feature of the confidential drier tests conducted by NIAE for grain-drier manufacturers.

Another application which usually follows on from a physical test is the computation of the performance of a drier over a wide range of operating conditions. The following example is for an eight-module mixed-flow drier in which up to half of the modules can be used for cooling instead of drying. The exact make and design of the drier are irrelevant for our purposes, which are simply to illustrate how the performance field can be defined. *Figure 10.2* shows the throughput of wet grain as a function of the drying air temperature for drying from 20% to 15% moisture content (wet basis; m.c.w.b.) and using up to four modules dedicated to

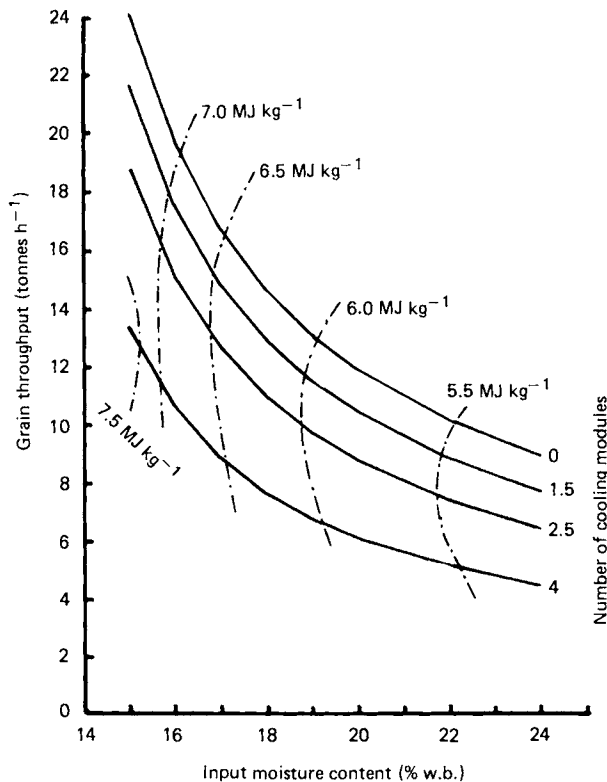


Figure 10.3 Computed effect of input moisture content on the grain throughput of an eight-module, mixed-flow drier when drying to 12% moisture content (w.b.) at a drying air temperature of 70°C and using from zero to four modules for cooling. Lines of equal specific heat consumption (-----) are also shown

cooling. Throughput increases with temperature but reduces with cooling modules. Given that it is necessary to cool the grain before discharge, then the number of modules necessary at a particular temperature can be judged from the plots of equal output grain temperatures. Finally, the plots of equal specific heat consumptions underline the advantage of using high drying air temperatures.

Figure 10.3 shows, for the same drier, the hyperbolic dependence of throughput on initial moisture content, this time when drying to 12% m.c.w.b., as might be the case for malting barley, and for a drying air temperature of 70°C. In this case, because it becomes increasingly difficult to remove moisture from dry grain, specific heat consumptions are higher than in the previous example, particularly at low initial moisture contents.

Thus, with the aid of a computer we can simulate the environment inside a grain drier and predict, at a most acceptable level of precision, its physical performance at steady state. The prediction of biological change is not so good, but work is under way to improve this. Real driers, however, seldom operate at steady state; normally the moisture content of the incoming wet grain is varying continuously and some form of continuous adjustment to the drier is necessary to maintain the required output moisture content. Thus we need to consider the unsteady state performance and control.

Drier control

There are two facets to the application of computers to the control of driers: (1) computer simulation provides an inexpensive means of developing and testing drier strategies; and (2) the cheap microprocessor offers potential for a controller of greater scope and flexibility than hitherto. But first we need to define the control problem and review existing solutions.

THE ERROR SIGNAL

Whether the controller be a human or an automatic electrical-mechanical device, its control action has to be based upon some estimate of the error or difference between the required and actual results. For a grain drier we wish to control the output moisture content and this is therefore the quantity for which, ultimately, we must derive an error signal. Unfortunately, grain moisture content is not an easy quantity to measure directly with any speed and it is more common to monitor some parameter closely correlated with the moisture content, with occasional correction from off-line moisture determinations.

The two rapid methods of estimating moisture content which are used sense either the electrical resistance or the capacitance of the grain. There are two problems with the resistance method. First, although it may give a consistent indication of moisture variation in a particular bulk of grain, its calibration may be affected by such factors as variety, season and geographical location. Secondly, the determinations need to be carried out on ground grain and this increases mechanical complexity. Nevertheless, there is a controller on the UK market which uses the resistance principle and which incorporates an automatic grinding system.

Grinding is not so important for moisture determination by capacitance, nor do varietal and seasonal differences have so much effect, but the readings are affected

by the abnormally dry surfaces of freshly dried grains and by variations in bulk density. In spite of these limitations, capacitance methods are employed on a number of commercially available controllers.

The physical property which is measured most easily is air temperature and it is probably true to say that it is the temperature of the exhaust air which is the most common source of the error signal on drier controls. This is not without good reason: over a wide range of initial moisture contents, the exhaust air temperature associated with a particular output moisture content changes little. Unfortunately, however, it changes most for low moisture removals. Thus, farmers who harvest the bulk of their grain at 18% m.c.w.b. or less, and many do, often find controllers based on exhaust air temperature sensing to be unsatisfactory. In batch driers the problem is overcome by switching to timed drying at low moisture removals.

The conclusion has to be that neither moisture sensing nor temperature sensing is entirely satisfactory and a combination of both might be desirable.

CORRECTIVE ACTION

Having derived an error signal, what action can be taken to return to the required moisture setting? Drying air temperature, which is easily monitored and relatively easily modulated, would seem a likely candidate. However, there are two problems. First, burners affordable on agricultural driers lack the flexibility to adjust easily over a wide range of temperatures. Secondly, running the drier at less than the safe operating temperatures reduces output and is normally less efficient. Thus, almost without exception, drying air temperature is controlled separately at a constant set value.

The amount of drying could also be varied by altering airflow rate, particularly if this could be done selectively along the drier. Once again, however, there are problems in burner flexibility and reduced output, even if the further problem of balancing flows were to be solved by the use of separate fans.

Thus, almost without exception, alteration in output moisture content is achieved by adjusting the grain flow rate, usually at the point of output from the drier.

CONTROL STRATEGIES

For purposes of discussion, drier control strategies can be conveniently divided into two types, feed-forward and feedback, although the best contain elements of both. The following summary draws heavily on the review by Whitfield (1985).

Feed-forward control

In feed-forward methods the control action is decided based on information derived at input to the drier. The simplest strategy is termed *set response*; this means that in response to some change in an input (e.g. the grain moisture content), the control parameter (e.g. grain output rate) will be altered according to some predetermined pattern. Its use for grain drying was investigated by Clifford (1972), who was adjusting not grain output rate but air temperature. Provided the

likely change in the input is known in advance, so that the most appropriate response can be decided, this method is ideal for moving from one steady state to another. However, it cannot cope with continually varying inputs.

The 'weighted-sum' method is used in a controller described by Olesen (1978) and used on the Danish Cimbria mixed-flow drier. A shift register, updated at successive sampling times, is used to memorize the value and position of each initial moisture content as it moves through the drier. The weighted mean of the initial moisture contents of grain residing in the drier is updated continually and used to adjust the output rate to that which would be required at steady state for a constant input of the weighted mean value. Clearly, some knowledge of the appropriate steady state setting is necessary and in practice it is necessary to add a slow feedback loop (Olesen, 1978).

A better method of deriving the feed-forward signal is to use a model of the drying process to predict the output moisture content and hence to derive the necessary adjustment. Although it may be possible to find a model which is more accurate than the empirical relation used in the 'weighted-sum' method, the prediction will still be subject to error and the method is of limited use on its own. However, combined with a feedback loop or as part of an adaptive system, it can provide a good method. In a computer-based analysis (Holtman and Zachariah, 1969a), simple linear and logarithmic models gave good control of a simulated drier. Because of its ease of use, the linear model was preferred and used in a subsequent study of the effect of performance index on output errors (Holtman and Zachariah, 1969b). Minimizing the sum of the squared errors in output moisture content was better than a zero under-drying index achieved by infinite weighting of under-drying and linear weighting of over-drying.

FEEDBACK CONTROL

In feedback control, the control action depends upon measurements at the output of the drier, or at the end of the drying bed (before the cooling bed). This has the advantage that the output error is measured rather than predicted. However, changes are not detected until they reach the sensor and this may be too late to correct for much of the grain in the drier.

On-off control is the simplest feedback control; it is not very effective but is the most common method used on agricultural driers, usually in conjunction with sensing exhaust air temperature rather than output moisture content. An exhaust air temperature below the set point indicates that the grain is too wet and the discharge is switched off; the grain now begins to over-dry, the exhaust air temperature rises above the set point and the discharge is switched on again. Upper and lower set points prevent excessive switching. The problem is that each 'off' cycle tends to induce a stable oscillation which does not die away. Agness and Isaacs (1967) presented an analysis from which they concluded that the method was more a control aid than an automatic control system; it is our impression that this is how it is most often used on farms. In practice, the discharge rate is set only slightly faster than the rate found by manual adjustment so that the 'on' periods are much longer than the 'off'. This copes with minor, but not major fluctuations in input. Apart from its simplicity, a virtue of the on-off method is that it can prevent any of the grain leaving the drier under-dried.

In *proportional* control, the discharge runs continually but its speed is altered by an amount proportional to the output error. The problem with this method is that the reduction in error signal as the set point is approached reduces the control action to the point where it may not be sufficient to return the output to the set point. Thus, there will always be a deviation or offset from the set point. This can be reduced by increasing the proportional correction, the gain, but with increasing possibility of instability. A better way to eliminate the steady state offset is to modify the control action by the integral of the error, i.e. *proportional plus integral* action.

In recent work at NIAE, Marchant (1985) has used a simple computer model of a grain drier to illustrate the behaviour of proportional, and proportional plus integral, control and to examine the problem of robustness. The following is a summary of his work.

The model drier can be envisaged as a tube of length x (in metres) in which the grain moves in a succession of layers of thickness Δx . Then, from thin-layer theory and ignoring heat transfer or airflow rate, the moisture change in each layer can be expressed as

$$(M' - M_e)/(M - M_e) = \exp.(-\Delta tk) \quad (10.12)$$

At each time step, the moisture content, M' , of the grain leaving the layer can be calculated from that entering, i.e. M . The grain is then moved through the drier, the distance travelled in the time step as calculated from the throughput rate. In this way the moisture profile through the drier is calculated continuously.

Although the model is a very simple one it does have three features which are important from the point of view of control: (1) there is a considerable time delay between the grain entering and leaving; (2) the amount of drying depends upon the time in the drier; and (3) the drying rate slows as the grain dries.

The behaviour of this drier running under proportional control is illustrated in *Figure 10.4*. Initially a steady state throughput is found at which an input moisture content of 0.25 dry basis (m.c.d.b.) gives the desired output of 0.17 m.c.d.b. With the control action switched off, the input is then subjected to a step decrease of 0.05 to 0.20 m.c.d.b; after one residence time a step decrease occurs in the output to a new steady state of <0.15 m.c.d.b. If this is repeated with the controller switched on and with a gain of 2, corrective action is taken and the output is returned towards 0.17 m.c.d.b. but with some offset. Increasing the gain to 5 reduces the offset but with increasing oscillation and signs of instability. In this case, the gain of 2 may appear to give an acceptable balance between accuracy and stability. However, if the step change is not a decrease but an increase to 0.30 m.c.d.b. then the response, for the same gain of 2, is very different. The system is now unstable with an oscillating output moisture content and a corresponding variable throughput.

The effect of adding an integral term is shown in *Figure 10.5*. Here, the gain is held at 0.5 and the output response to the step decrease is shown for three values of the integral time, T_i , where $T_i = 0$ represents the proportional-only control, similar to that of *Figure 10.4*. At $T_i = 60$ min, the output moisture content begins to return to 0.17 (m.c.d.b.) but at a very low rate. $T_i = 15$ min gives a much faster and seemingly acceptable response, but once again a step increase to a moisture content of 0.30 (m.c.d.b.) on input renders the system unstable.

Thus, both controllers are sensitive to the conditions under which they are used or, in control terms, are not *robust*. One solution would be for the operator to

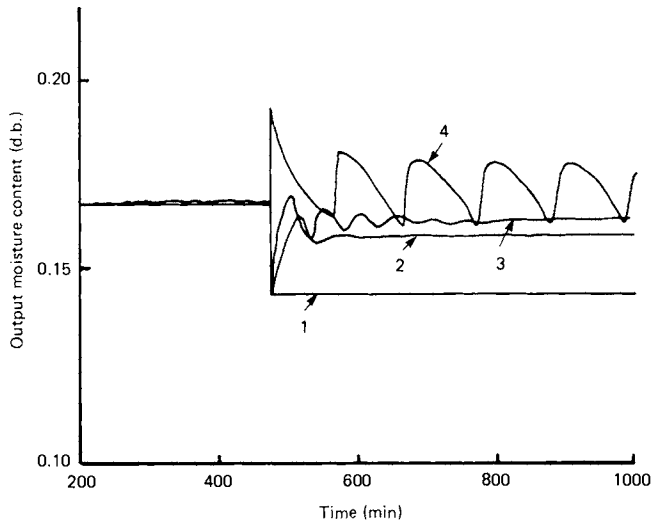


Figure 10.4 Computed response of a simple drier with *proportional only* control. In the initial steady state a constant input of 0.25 moisture content (d.b.) is reduced to 0.17 d.b. on output. The curves show the effect of a step decrease on input to 0.20 m.c.d.b. for (1) no control, i.e. gain, $k = 0$; (2) $k = 2$; (3) $k = 5$; and (4) the effect of a step increase in input to 0.30 moisture content (d.b.)

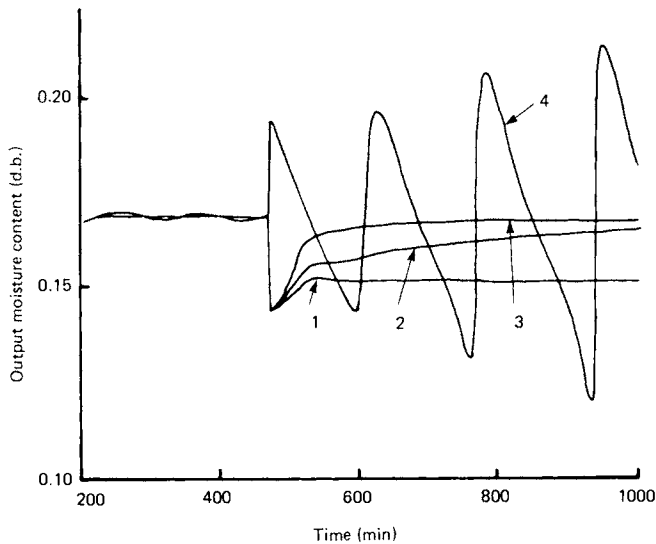


Figure 10.5 Computed response of a simple drier with *proportional plus integral* control. In the initial steady state a constant input of 0.25 moisture content (d.b.) is reduced to 0.17 on output. With the proportional gain, $k = 0.5$, the curves show the effect of a step decrease in input to 0.20 moisture content (d.b.) when (1) integral time, $T_i = \infty$, i.e. proportional only; (2) $T_i = 60$ min; (3) $T_i = 15$ min; and (4) the effect of a step increase in input to 0.30 moisture content (d.b.) when $T_i = 15$ min

adjust the gain and integration interval during the course of drying. Our experience suggests that this would not be feasible. Not only is it not obvious what to adjust, or by how much, but also the effect of any adjustment is not easily assessed when it may not be manifest for an hour or two. The real solution lies in deriving a control loop with constant sensitivity and the key to doing this lies in the exponential nature of the drying process.

AN IMPROVED CONTROLLER

If we make a further simplification to our model on page 137, and assume that k and M_e are constant, then we can write

$$(M_{out} - M_e)/(M_{in} \times M_e) = \exp.(-kt) = \exp.(-kx/V) \quad (13)$$

where V = velocity through model drier (m s^{-1}). Letting $k = 0.025$ and M_{in} , M_{out} and M_e be 0.20, 0.17 and 0.085 m.c.d.b., respectively, then we can calculate the required velocity, V , to be 0.0827 m s^{-1} . If the error signal changes to 0.01 m.c.d.b. then a gain of 2 will increase V to 0.1027 m s^{-1} . Now, if M_{in} is still 0.20 m.c.d.b., substitution of the new velocity into *Equation 10.13* gives an M_{out} of 0.1752 m.c.d.b., i.e. an increase of 0.0052 m.c.d.b., and we can calculate the sensitivity as $0.0052/0.01$, i.e. 0.52. However, if we begin with an M_{in} of 0.30, then the initial steady state velocity for an M_{out} of 0.17 m.c.d.b. would be 0.0269 m s^{-1} . Now, if the error changes to 0.01 d.b., then the same gain will alter the velocity V to 0.0469 m s^{-1} and substitution back into *Equation 10.13* gives $M_{out} = 0.2111$. This time the change is 0.0411 m.c.d.b. and the sensitivity = $0.0411/0.01$, i.e. 4.1, which is eight times the previous sensitivity. It is not surprising, therefore, that the control system behaves differently with different operating conditions.

A loop with constant sensitivity can be achieved by writing *Equation 10.13* in logarithmic form

$$\ln(M_{in} - M_e) - \ln(M_{out} - M_e) = kx/V \quad (10.14)$$

Letting $N_{in} = \ln(M_{in} - M_e)$, $N_{out} = \ln(M_{out} - M_e)$ and $R = 1/V$, we obtain

$$N_{in} - N_{out} = Rkx \quad (10.15)$$

If we now set up a feedback loop based on *Equation 10.15* the error is the difference between the desired N_{out} and the actual N_{out} , and the product of the error and the gain are applied to R before it is converted to V . The system thus operates by measuring the logarithmic moisture content and controlling the inverse velocity to suit. Because of the linear form of *Equation 10.15*, the proportional change in the feedback signal for a given change in the error is independent of the value of input moisture content. The control sensitivity is thus constant and the controller should be robust.

The simulated performance of the model drier when controlled on the basis of *Equation 10.15* is shown in *Figure 10.6*. Four operating conditions are shown. In the first two the drier is stabilized for an input moisture content of 0.25 m.c.d.b. and a target of 0.17 m.c.d.b. The input grain changes in one case to 0.20 m.c.d.b. and in the other to 0.30 m.c.d.b. In the second two conditions, the initial input is 0.22 m.c.d.b., the target is 0.13 m.c.d.b. and the input changes are to 0.17 and 0.28 m.c.d.b. It can be seen that a good balance is obtained between stability and speed

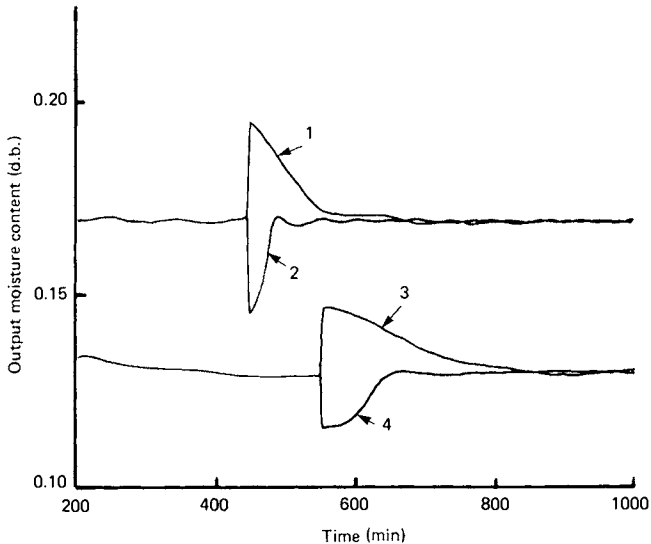


Figure 10.6 Computed response of a simple drier using the robust control algorithm of *Equation 10.15*. The curves show the effect of a stepped increase (1) and (3) and stepped decrease (2) and (4) of 0.05 m.c.d.b. on initial steady states of from 0.25 to 0.17 and 0.22 to 0.13 m.c.d.b., respectively

of response. The output moisture content returns to the target value after the input disturbance and the performance is preserved over a wide operating range.

It is interesting that the control algorithm used to derive *Figure 10.6* has the form

$$R = R_{-1} + 23E - 19E_{-1} \quad (10.16)$$

where the negative suffixes refer to the values in the preceding sampling interval and E = error for control. Clearly, neither the form of *Equation 10.16* nor the numbers contained in it are obvious, and it could not have been developed without using a proper control system design technique. In this case, the method was that of frequency domain compensation using a describing function to derive the frequency response of the drier (see, for example, Shinnars, 1964). In order to use such methods for commercial-scale driers a quantitative description of the drier dynamics are required and these are best derived using the mathematical models of drying described on pages 128–130. At NIAE, a controller has been designed for an experimental mixed-flow drier and experimental evaluation is under way.

OTHER ASPECTS OF DRIER CONTROL

Clearly, the next generation of drier controllers will have considerable computing power and they will almost certainly be used to perform the other tasks necessary to control the complete grain-handling/drying plant. These will include sequential switching of conveyors, elevators and burners, alarm and shut-down procedures, and information and records for the operator.

Conclusions

In the early 1960s, the computational power of the digital computer broke the *impasse* which had been preventing the application of drying physics to commercial-scale driers. Since then, computer simulation has been applied with considerable success to the design, operation and testing of grain driers. Current research should lead to improved prediction of the physical conditions inside driers in which airflow is highly non-linear, and of changes in grain quality. Dynamic versions of the drier models are being used in the development of drier controllers which will themselves employ microcomputers, not only to perform control calculations but also to perform other switching operations, monitoring and recording.

References

- AGNESS, J.B. and ISAACS, G.W. (1967). Grain drier control based on exhaust temperature sensing. *Transactions of the American Society of Agricultural Engineers*, **10**, 110–113
- BAKKER-ARKEMA, F.W., BICKERT, W.G. and MOREY, R.V. (1967). Simultaneous heat and mass transfer during grain drying. *Landtechnik Forschung*, **17**, 175–180 (In German)
- BOYCE, D.S. (1965). Grain moisture and temperature changes with position and time during through drying. *Journal of Agricultural Engineering Research*, **10**, 333–341
- BOYCE, D.S. (1966). Heat and moisture transfer in ventilated grain. *Journal of Agricultural Engineering Research*, **11**, 255–265
- BRUCE, D.M. (1984). Simulation of multiple-bed concurrent-, counter-, and mixed-flow grain driers. *Journal of Agricultural Engineering Research*, **30**, 361–372
- CLIFFORD, W.H. (1972). 'Simulation and open-loop control of a concurrent drier.' PhD Thesis, Michigan State University
- ELLIS, R.H. and ROBERTS, E.H. (1980). Towards a rational basis for testing seed quality. In *Seed Production*, pp. 605–635. Ed. by Hebblethwaite, P.D. Butterworths, London
- ELLIS, R.H. and ROBERTS, E.H. (1981). The quantification of ageing and survival in orthodox seeds. *Seed Science and Technology*, **9**, 373–409
- FORTES, M., OKOS, M.R. and BARRETT, J.R. (1981). Heat and mass transfer analysis of intra-kernel wheat drying and rewetting. *Journal of Agricultural Engineering Research*, **26**, 109–125
- HOLTMAN, J.B. and ZACHARIAH, G.L. (1969a). Continuous cross-flow modeling for optimal control. *Transactions of the American Society of Agricultural Engineers*, **12**, 430–432
- HOLTMAN, J.B. and ZACHARIAH, G.L. (1969b). Computer controls for grain dryers. *Transactions of the American Society of Agricultural Engineers*, **12**, 433–437
- M'EWEN, E. and O'CALLAGHAN, J.R. (1954). Through drying of deep beds of wheat grain. *The Engineer*, Dec. 10, 817–819
- MARCHANT, J.A. (1985). Control of high temperature continuous-flow grain driers. *Agricultural Engineer*, **40**, 149–154
- MILLER, P.C.H. and WHITFIELD, R.D. (1984). The predicted performance of a

- mixed-flow grain drier. *Journal of Agricultural Engineering Research*, **30**, 373–380
- NELLIST, M.E. (1974). 'The drying of ryegrass seeds in deep layers.' PhD Thesis, University of Newcastle-upon-Tyne
- NELLIST, M.E. (1979). Crop drying and mathematical models. In *Proceedings of Operational Research Workshop*. Report No. 32. NIAE, Silsoe
- NELLIST, M.E. (1981). Predicting the viability of seeds dried with heated air. *Seed Science and Technology*, **9**, 439–455
- NELLIST, M.E. (1986). Modelling the performance of a cross-flow drier. *Journal of Agricultural Engineering Research* (in press)
- OLESEN, H.T. (1978). *Automatic Control Arrangements for Continuous Drying Plant*. British Patent Specification (1502710)
- PAGE, G. (1949). 'Factors influencing the maximum rates of air drying shelled corn in thin layers.' MSc Thesis, Purdue University
- PARRY, J.L. (1983). 'Mathematical modelling and computer simulation of heat and mass transfer in agricultural grain drying.' PhD Thesis, Cranfield Institute of Technology
- PARRY, J.L. (1984). *Mathematical Modelling and Computer Simulations of Heat and Mass Transfer in Agricultural Grain Drying. A Review*. Report No. 44. NIAE, Silsoe
- PIERCE, R.O. and THOMPSON, T.L. (1981). Energy use and performance related to cross-flow dryer design. *Transactions of the American Society of Agricultural Engineers*, **24**, 216–220
- ROBERTS, E.H. (1960). The viability of cereal seed (in storage) in relation to temperature and moisture. *Annals of Botany*, **24**, 12–31
- SHARP, J.R. (1982). A review of low temperature drying simulation models. *Journal of Agricultural Engineering Research*, **27**, 169–190
- SHINNERS, S.M. (1964). *Control System Design*. Wiley, New York
- THOMPSON, T.L., PEART, R.M. and FOSTER, G.H. (1968). Mathematical simulation of corn drying—a new model. *Transactions of the American Society of Agricultural Engineers*, **11**, 582–586
- VAN ARSDEL, W.B. (1955). Simultaneous heat- and mass-transfer in a non-isothermal system; through-flow drying in the low-moisture range. In *Mass-transfer: Transport Properties*, pp. 47–58. American Institute of Chemical Engineering, Chemical Engineering Progress Symposium Series, No. 16
- WHITFIELD, R.D. (1985). 'Control strategies for continuous-flow grain driers—a review.' Divisional Note DN 1245, NIAE, Silsoe

COMPUTER CONTROL OF SULPHUR DIOXIDE FUMIGATION IN A STUDY OF CROP RESPONSE TO POLLUTION

J.J. COLLS, C.K. BAKER and G. SEATON
Nottingham University, UK

Introduction

Greenwood *et al.* (1982) described a system for exposing a single area within a commercial wheat crop to controlled elevations of sulphur dioxide concentration. This chapter describes the expansion of that system to three fumigated plots, gives examples of the performance of the system in controlling SO₂ concentrations, and presents grain yield results for the 1983/84 season when winter barley was being tested for sensitivity to SO₂.

The effects of air pollutants on plants are many and various; for example, Unsworth and Ormrod (1982) and Koziol and Whatley (1984) give descriptions of the detailed biological and biochemical consequences of pollutant exposure. Plant damage by air pollutants was first identified in an acute form close to industrial sources which generated very high ground-level concentrations. It has since been shown to be far more widespread, and a range of pollutants is now known to cause reduced growth and yield in agricultural and horticultural crops. Three experimental approaches have been used to explore these relationships.

In closed chamber experiments, small numbers of plants are grown in carefully controlled conditions in which temperature, humidity, pollutant concentration and other variables can be altered at will. The conditions, though, are not like the real world, and it is now known that plant responses in more natural environments may be very different (Roberts, 1984).

There is thus a need to control conditions to some extent and yet to represent natural environmental fluctuations more completely. This has resulted in the 'open top chamber', in which a larger number of plants is grown in a vertical cylinder with transparent walls and no roof (Heagle, Body and Heck, 1973). Ambient air is ducted into the base of the cylinder by a fan. Pollutants already in the air can be removed by activated charcoal or augmented by controlled infusion. There is still a tendency for internal air temperatures to be higher, and solar radiation levels lower, than those prevailing outside the chamber. In addition, some of the expected control over pollutant concentration is lost due to variable turbulent mixing down through the open roof.

As a consequence of the deficiencies of both closed and open-top chambers in simulating natural conditions, the next step toward reality was the development of field fumigation systems with which larger crop areas could be exposed to low

pollutant concentrations. The first of these was established in France in the early 1970s for exposing trees to low concentrations of SO₂ (De Cormis, Bonte and Tisne, 1975). Since then, equipment has also been developed in the USA and in the UK to fumigate areas of crop at low pollutant concentrations, while interfering as little as possible with all other aspects of the plants' environment (McLeod, Alexander and Hatcher, 1983; Lauenroth and Preston, 1984). The work of Lauenroth and Preston was a particularly complete study of the overall ecological impact of raised SO₂ concentrations on a mature prairie grassland, in which changes to the soil and microorganisms were studied, as well as direct effects on the plants themselves.

Plants in the open are normally bathed in pollutant from above. Concentrations will tend to be quite uniform spatially over areas of a few hectares, with short-term temporal variations which are highly correlated from point to point. The exposure system of Lauenroth and Preston, mentioned *above*, operated on a constant release basis—that is, the release rate of SO₂ was fixed at a level designed to give an appropriate SO₂ concentration, well away from the release point, under average windspeed and stability conditions. As a consequence, the actual SO₂ concentration inevitably fluctuates through a very wide range, with high peaks under low-windspeed, high-stability conditions and low peaks under high-windspeed, low-stability conditions. The SO₂ was released from many points within the crop, so that the spatial uniformity was rather poor. Because of the constant release rate there is also little relation between the imposed elevation and variations in the ambient concentration.

The Sutton Bonington system

DESIGN

The Sutton Bonington fumigation philosophy, described by Greenwood *et al.* (1982), was designed to overcome the limitations of other methods while still satisfying the principal requirements: spatial uniformity over a sufficiently large number of plants to obtain statistically valid results; average concentrations within the range experienced in polluted areas of Europe; and concentration frequency distributions which related to the natural fluctuations found in ambient SO₂ levels. The present fumigation system, which is largely based on the original 1980 design, is summarized below.

Figure 11.1 shows an individual treatment area. Liquid sulphur dioxide from the supply bottle is vaporized at a pressure of 1 bar, and flows via a motorized needle valve, rotameter and solenoid on/off valve to the supply tubing. This pure SO₂ is mixed with about 12 $\ell \text{ min}^{-1}$ of ambient air supplied by a small centrifugal fan, the diluted gas then passing into a 20 m length of 35 mm diameter polypropylene pipe, which is blocked at the far end. A 2.4 mm hole is pierced every metre down the length of the pipe. Each pipe thus acts as an effective line source of SO₂ and is positioned horizontally about 0.2 m above the crop and moved up on posts as the crop grows during the season. Four independent line sources make up one fumigation square. Early tests showed that the observed profiles downwind of such a line source agreed closely with those predicted by gas dispersion models. It was also found that the gradient of concentration with distance from the pipe would provide uniform exposure from 5 m to about 15 m from the source. Thus, the outer

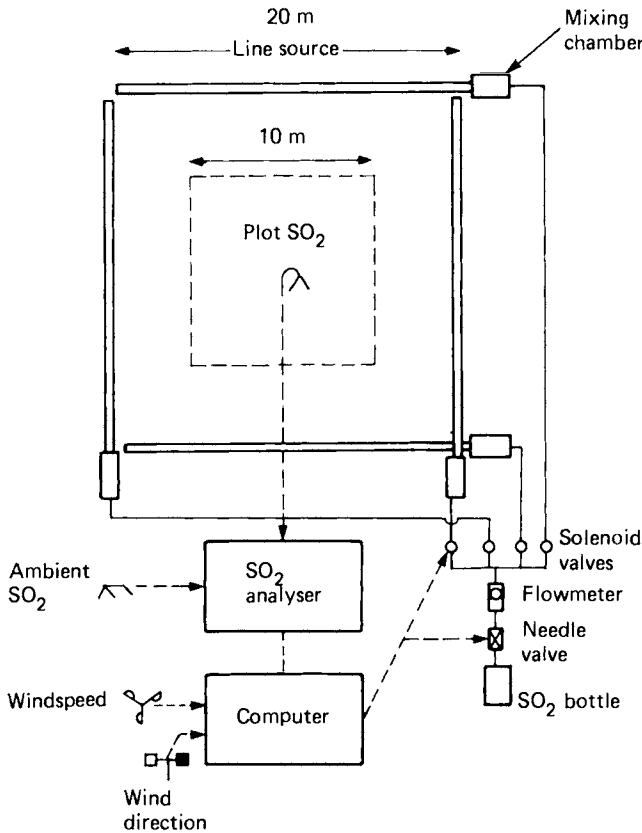


Figure 11.1 Schematic arrangement of the SO₂ supply, release and control equipment for one fumigation plot

5 m of each fumigation square serves entirely as a mixing region; all crop analysis is made on plants from within the central 10 m × 10 m square.

OPERATION

There are many possible ways in which the fumigation regime could be specified—for example, as a constant total SO₂ concentration or as a constant multiple of the ambient concentration. In this experiment the target concentration is defined as a constant elevation above the prevailing ambient level, which is itself measured at an upwind point. In 1983/84 the three plots were treated at elevations of 200, 100 and 50 ppb above ambient, with the layout shown in *Figure 11.2*. (In the 1984/85 season the corresponding concentrations were 120, 80 and 40 ppb.) The system is controlled by a PET microcomputer which makes three levels of control decision based on windspeed, wind direction and SO₂ concentration.

Windspeed

It has been found by experience that very low windspeeds cause erratic system response because they are associated with variable wind directions. In addition,

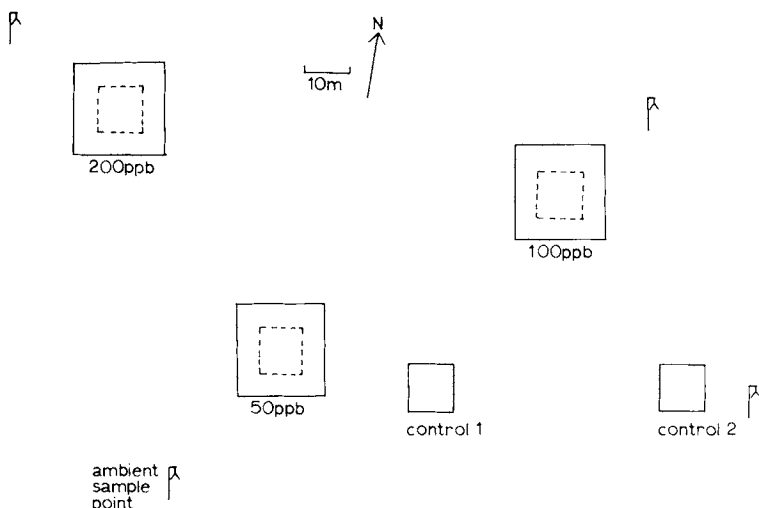


Figure 11.2 Layout of the three fumigation plots, two control plots and four ambient sampling points for 1983/84

they may not guarantee sufficient dilution of the line source gas mixture (which comes out through the holes at a concentration of several thousand ppm) during its passage across the 5 m mixing region to prevent permanent injury to the plants. A cup anemometer signal is therefore used to inhibit fumigation below a windspeed of 1 m s^{-1} , which is calculated as a running mean over 30 min.

Wind direction

A windvane signal is used to decide which lines should release gas. If the wind is blowing from within ± 30 degrees of the perpendicular to a pipe, then that line alone is opened. If the direction is from within ± 15 degrees of a diagonal, then the two adjacent upwind pipes are opened. There are therefore never more than two pipes open on any one plot. A Gaussian dispersion program has been used to calculate the concentrations over the whole fumigation square resulting from any specified combination of release rate, wind direction and atmospheric stability. *Figure 11.3(a)* gives the contours for the 100 ppb plot when the wind is due west and one pipe is releasing, while *Figure 11.3(b)* shows the same situation as an isometric profile. *Figure 11.4(a)* and *(b)* show the corresponding contours for a south-westerly wind with equal SO₂ release from the south and west pipes. The most uniform distribution is clearly achieved in the first case. Nevertheless, the distribution in the second example is still acceptable over the central 10 m square, although a lot of SO₂ is wasted along the margins of the plot.

Concentration difference

Filtered air samples are pumped continuously through inert sample lines from fumigation sample points in the centre of each plot and from four ambient sample

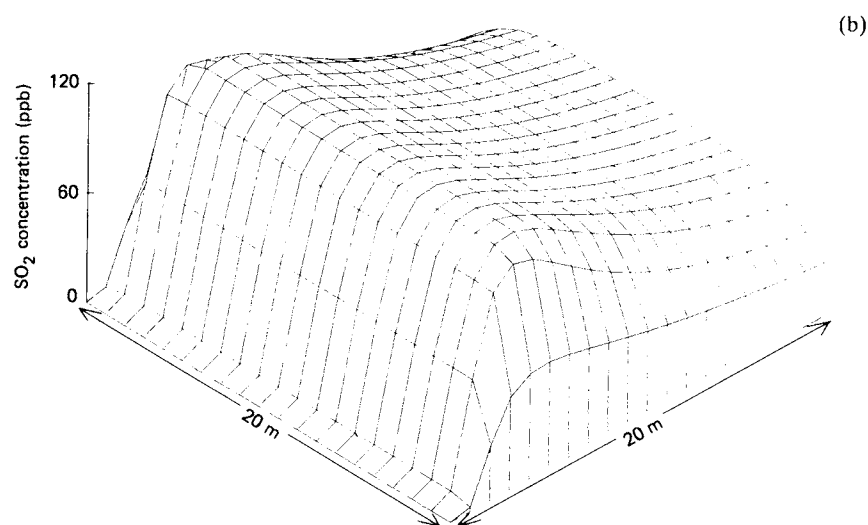
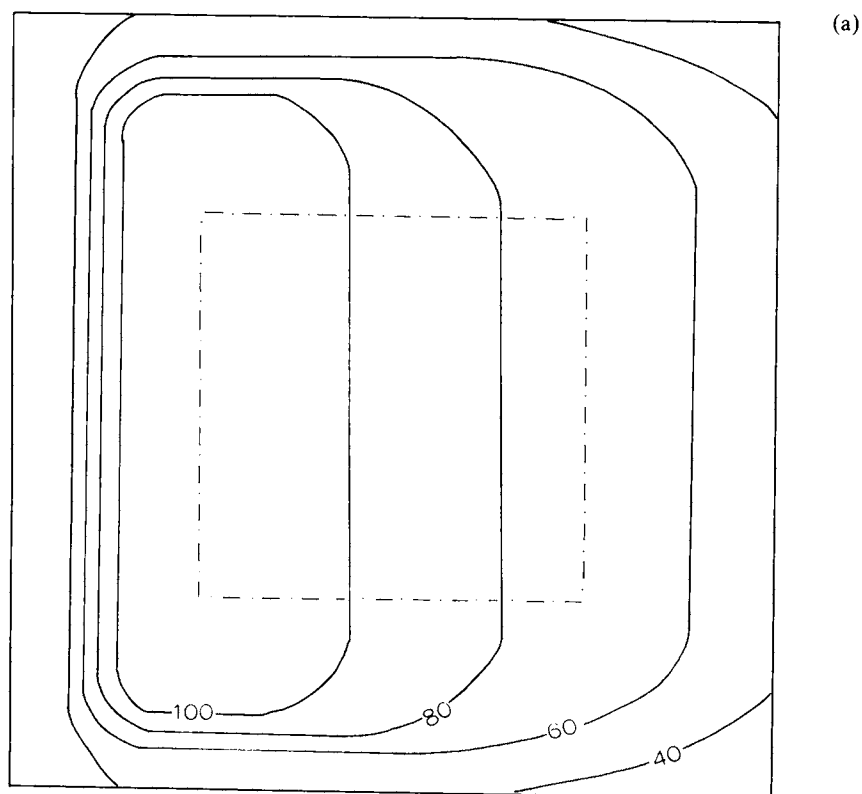


Figure 11.3 (a) Calculated SO_2 contours across the plot when the wind is blowing from the west. The west pipe only is releasing gas. (b) Isometric contours

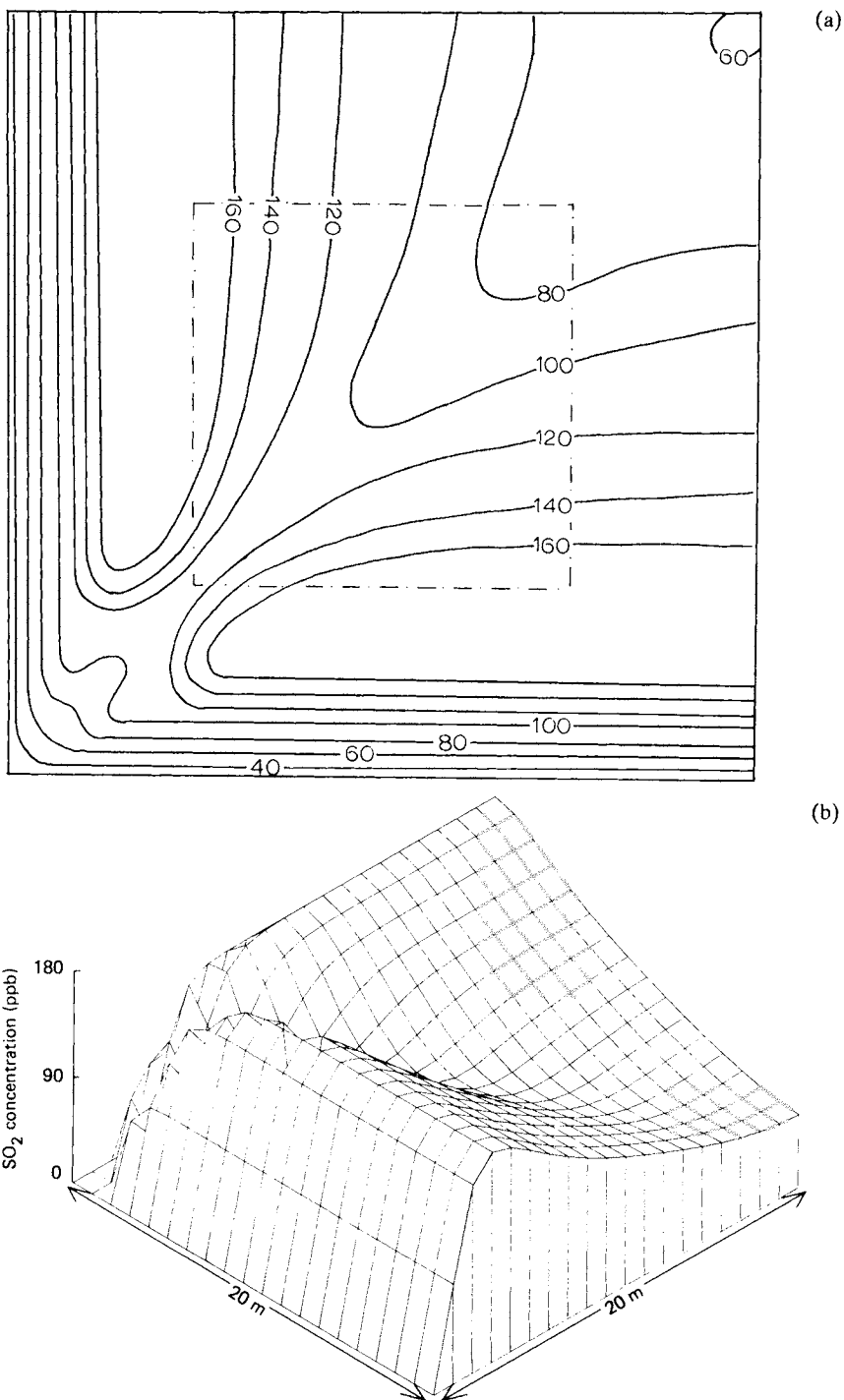


Figure 11.4 (a) Calculated SO_2 contours across the plot when the wind is blowing from the south-west. The south and west pipes are releasing gas. (b) Isometric contours

points round the edge of the whole system. A Meloy SA285 flame photometric sulphur analyser is switched by the computer between the appropriate (upwind) ambient sample point and a treatment sample point. The computer compares the measured concentration from the treatment sample with the target concentration, which will be equal to the ambient plus the appropriate fixed elevation. It then adjusts the motorized needle valve to increase or decrease the release rate as required. The system operates on a 20 min cycle, spending 5 min each on the ambient reading and the three treatment readings. Two minutes are allowed for the analyser to stabilize on the new sample; the following 3 min are used to form an average value. Each treatment flow rate is adjusted immediately after the concentration measurement for that square, and remains fixed until its turn comes round again. The plastic tubing which supplies SO_2 to the release lines is all the same length for any one treatment; any pair of supply pipes is therefore dynamically balanced and one needle valve can be used to supply both pipes with SO_2 .

Two examples of the short-term behaviour of the system are shown in *Figures 11.5 and 11.6*. In the first case, the wind blew very steadily from the north-east sector during the 24 h period. From 1200 to 1800 there was a high but steady

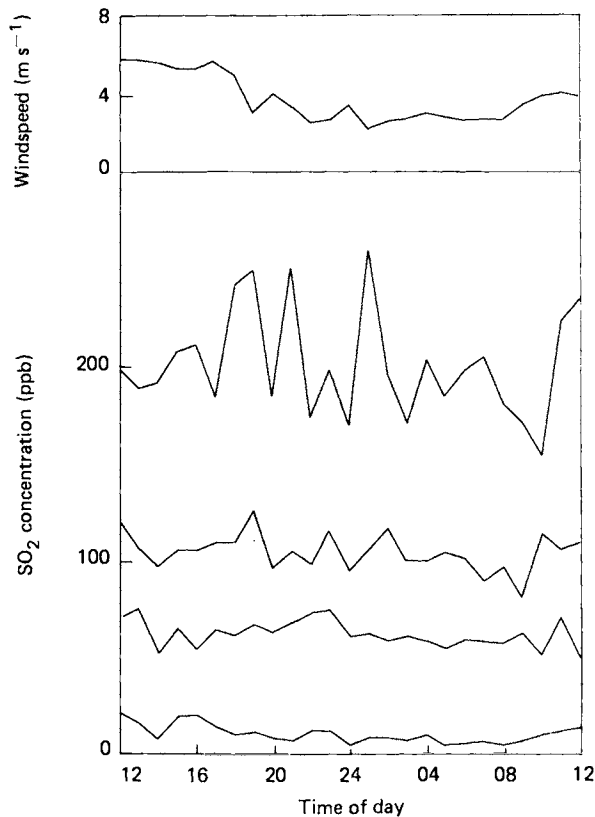


Figure 11.5 Performance of the fumigation system over a 24 h period when the wind direction was steady and there were two periods of steady windspeed

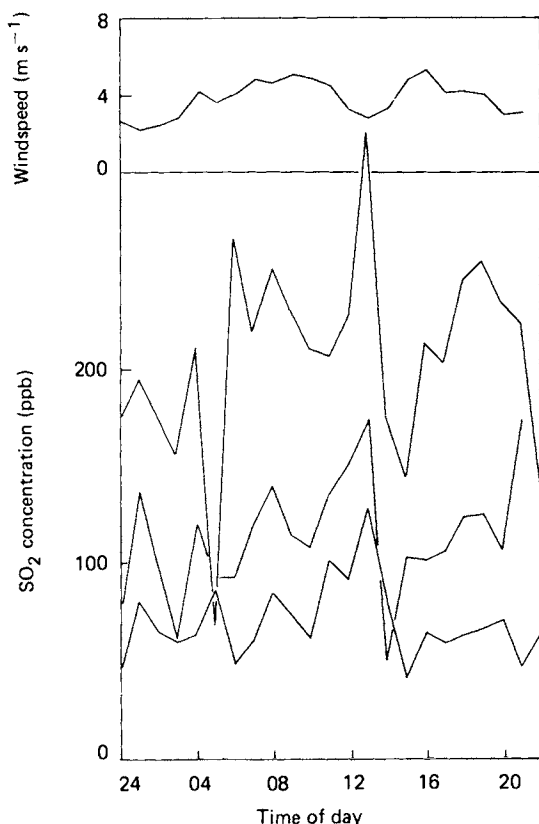


Figure 11.6 Performance of the fumigation system over a 24 h period when both windspeed and wind direction were unsteady

windspeed; from 0100 to 0800 there was a low but steady windspeed. Under these conditions the system settles down, does not need to switch line sources and only makes small adjustments to flow rate. The treatment SO₂ concentrations are therefore quite smooth. In the intervening period of changing windspeed, the system responds with greater variations in concentration, although the average levels remain close to target. The second example shows how a continuously varying windspeed and direction can produce larger fluctuations, although again the average levels remain close to target.

RESULTS FOR THE 1983/84 SEASON

In the 1983/84 season the fumigation system was operated within a flat 14 ha field of winter barley (*Hordeum vulgare*, cv 'Igri'). The crop was sown on 21 October 1983 and had emerged by 6 November 1983. Automatic fumigation, at concentrations of 200, 100 and 50 ppb above ambient, began on 24 January 1984 and continued until 8 July 1984. The crop was harvested on 28 July 1984. In the following sections we will examine both the long-term and the short-term performance of the system in meeting the fumigation objectives.

Table 11.1 FUMIGATION SYSTEM PERFORMANCE

Growing season	=	245 days	=	70560 scans
Fumigation period	=	166 days	=	47808 scans
System scans	=	29505	=	62% availability
Fumigation scans	=	20570	=	43% of fumigation period
			=	30% of growing season

Table 11.2 TARGET AND MEASURED SO₂ CONCENTRATIONS (ppb)

Nominal target elevations	200	100	50
Achieved elevations during fumigation	181	91	47
Average elevation over fumigation period	78	39	12
Average elevation over growing season	54	27	14
Average total concentrations during fumigation	196	108	63
Average total concentrations over fumigation period	93	55	36
Average total concentrations over growing season	69	43	29

Note: The average ambient SO₂ concentration was 15 ppb

Table 11.1 summarizes the seasonal operation. One 'scan' is an individual 5 min cycle during which the SO₂ concentration from one treatment or the background is being measured. During the fumigation period (24 January–8 July 1984), 47808 scans were possible. Of these, 29505 were actually carried out, the remainder consisting of system failures, bad data and other faulty records. This represents 62% availability. Of these actual scans, 20570 were fumigation scans, the remainder being periods when the running mean windspeed was below 1 m s⁻¹. Thus, the crop was fumigated for about 43% of the fumigation period, which in turn represents 30% of the growing season. *Table 11.2* shows that the average concentration elevations achieved in the treatments during fumigation were 181 (±91), 91 (±54) and 47 (±24) ppb for the nominal 200, 100 and 50 ppb treatments, respectively. The average ambient concentration over the same period was 15 (±22) ppb. Hence the average total concentrations at the centre of each treatment, during fumigation, were 196, 108 and 63 ppb, respectively.

Figure 11.7 gives cumulative frequency distributions for the total concentrations measured on the three treatments and for the ambient concentration. The background distribution is clearly log-normal throughout its range. The three treatment distributions are log-normal above 10–15%, but show a higher probability of low concentrations than predicted. The similar characteristics for the three distributions reflect the similarity of construction and operation of the three treatment plots.

Wind data for the fumigation period gave the directional distribution shown in *Figure 11.8*. Peak frequencies were from the north-east and the north-west, with contrasting minima from north and south. The average windspeed was 3.0 m s⁻¹ at a height of 1.5 m. The distribution of ambient SO₂ with wind direction (*Figure 11.9*) was quite flat—as is to be expected in the rural East Midlands—though peaks are identifiable from local sources at 15 degrees (Ratcliffe-on-Soar power station), 195 degrees (Sutton Bonington boiler house) and 270 degrees (Castle Donington power station).

The 'wind rose' (shown in linear form in *Figure 11.8*) applies for the whole fumigation period, whether actually fumigating or not. By combining the corresponding rose for times of fumigation only (*Figure 11.10*) with the calculated

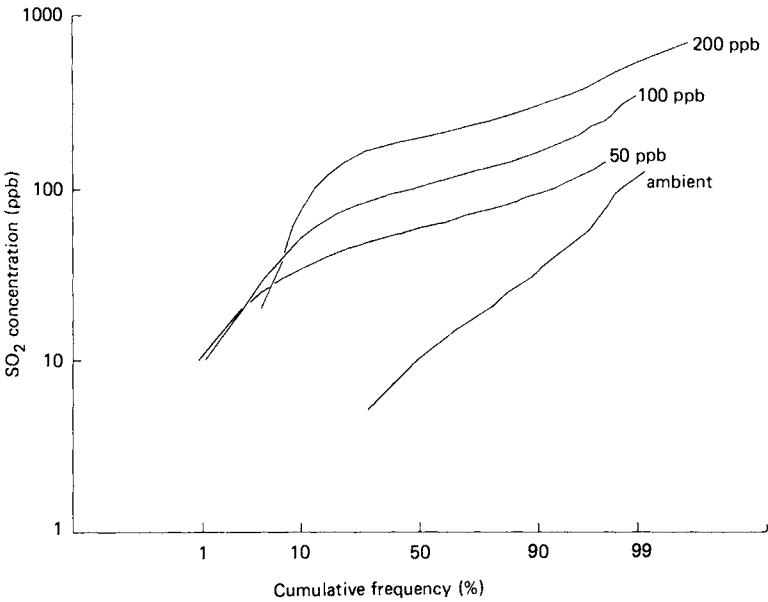


Figure 11.7 Cumulative frequency distributions of the ambient SO_2 concentration and of the total concentration at the three fumigated plots

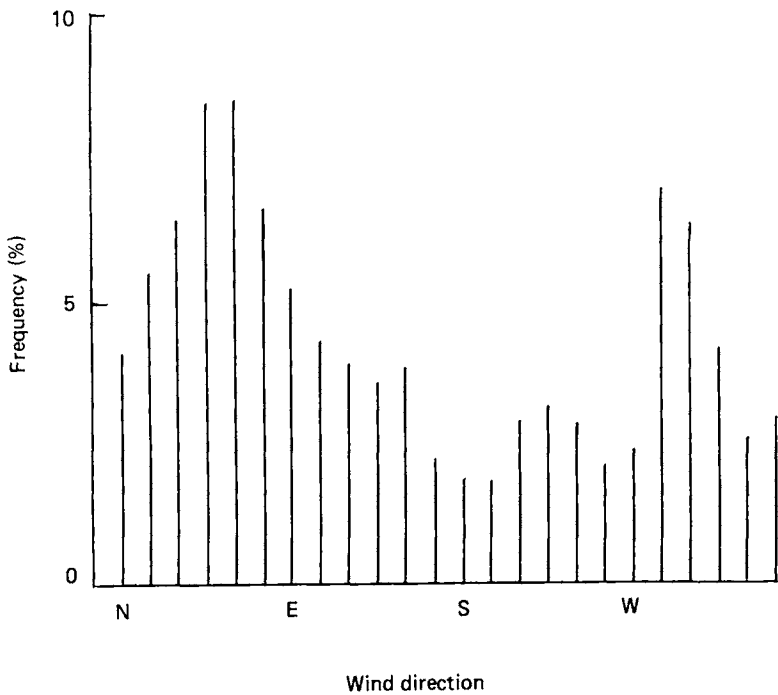


Figure 11.8 The frequency with which the wind blew from different directions during the fumigation period

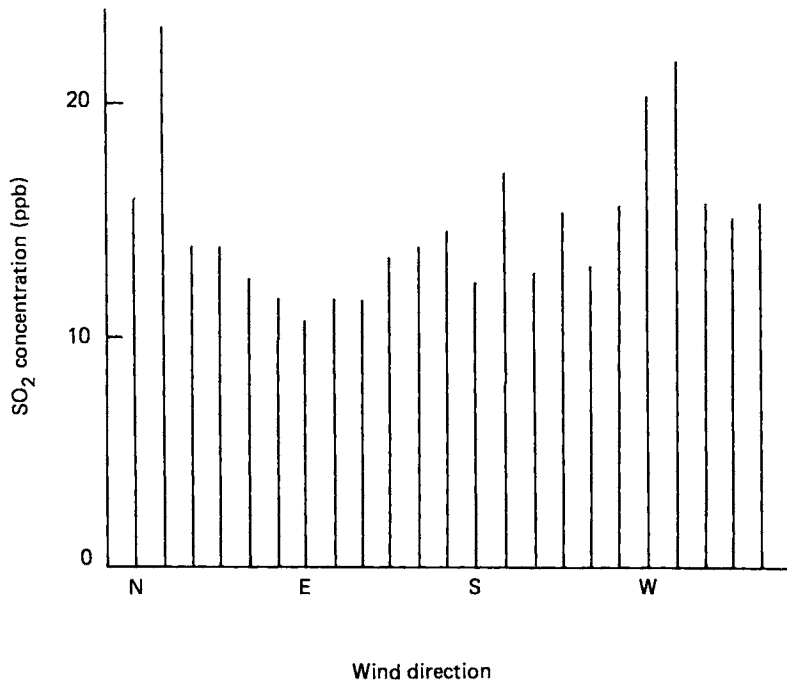


Figure 11.9 The variation of average ambient SO_2 concentration with wind direction

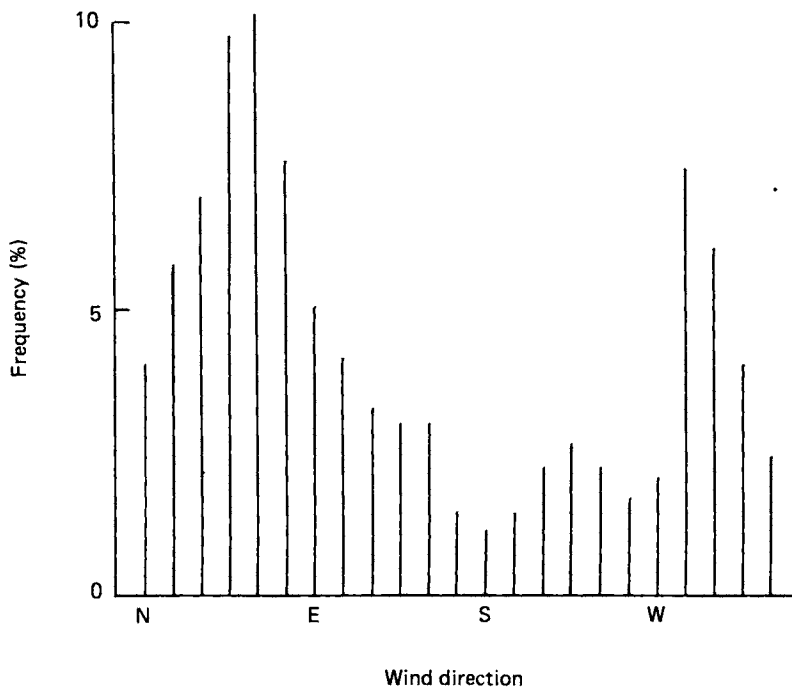


Figure 11.10 The frequency with which the wind blew from different directions while fumigation was occurring

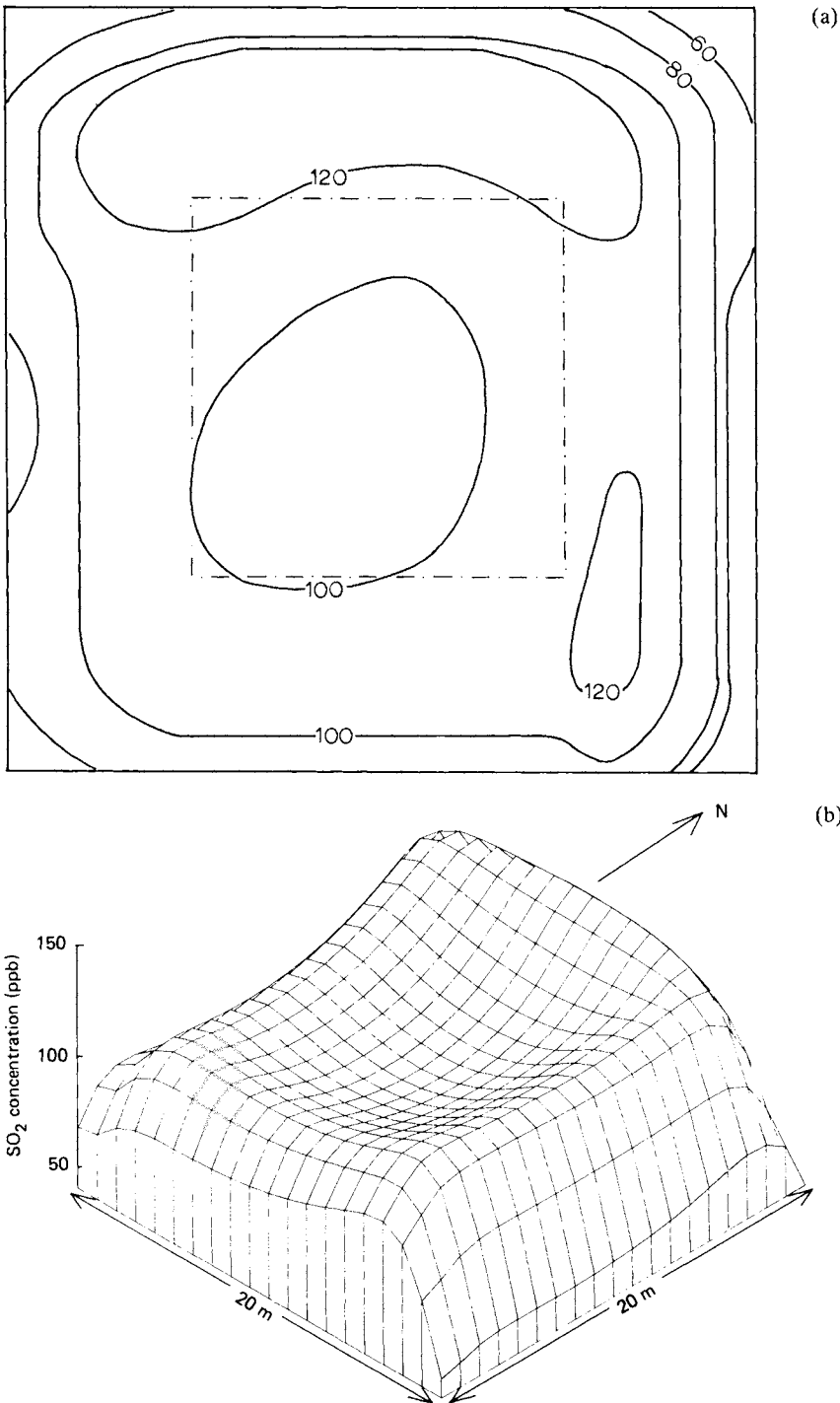


Figure 11.11 (a) Calculated SO₂ elevations over the fumigation period. (b) Isometric contours

spatial distributions of SO_2 elevation for particular wind directions, as shown in *Figures 11.3 and 11.4*, we have also derived the distribution of average SO_2 elevation across the plots throughout the fumigation period (*Figure 11.11a,b*). It can be seen that this distribution was quite flat—in fact the standard deviation of elevations over the 10 m square was within 7% of the central mean value. This confirms that the original goal of uniform fumigation was indeed achieved. The higher concentrations found close to the north and east line sources correspond to the higher proportion of winds blowing from the north-east sector. Equivalent lines for all three plots were all switched simultaneously—hence the shape of the average distribution calculated *above* will apply equally to the 200, 100 and 50 ppb plots.

Calculations have also been made to find the influence of the line sources on the remainder of the barley field, with particular reference to the control plots. Use of a Gaussian dispersion program, in conjunction with the wind rose during fumigation time, showed that the average SO_2 elevation on Control 1 was 10 ppb, and that on Control 2 was 4 ppb.

Variations during the fumigation period

In this section we shall examine the month-by-month variations in fumigation which occurred between January and July 1984. The monthly average elevations (during fumigation time only) are shown in *Figure 11.12*. In order to represent achieved fumigation, the 'dose' of average concentration multiplied by period of exposure is used (Halbwachs, 1984). Although the dose would in practice be modified by a variable factor, related to canopy conductance, we do not have sufficient supporting information to estimate this. The total ambient dose over the growing season of 245 days amounted to some 4100 ppb days, and the total doses (elevation + ambient) accumulated for the three treatments were 16900, 10600 and

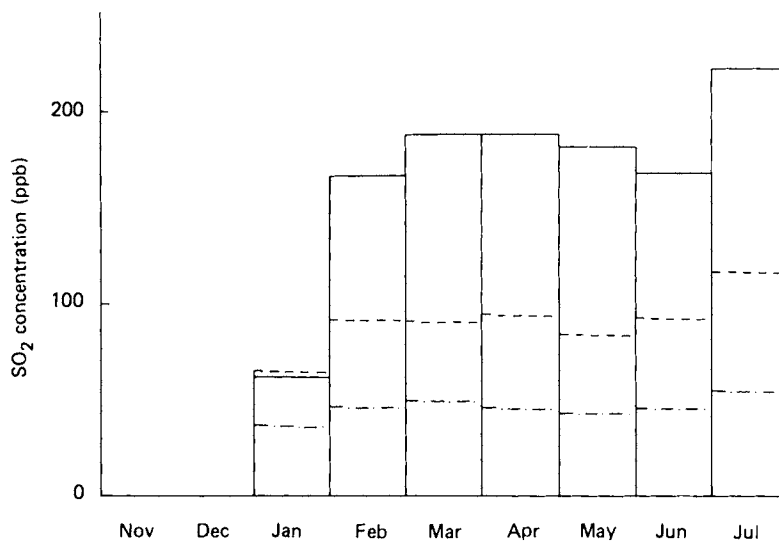


Figure 11.12 Monthly average SO_2 elevations (during fumigation) at the three plots over the growing season. — = 200 ppb; --- = 100 ppb; -.- = 50 ppb

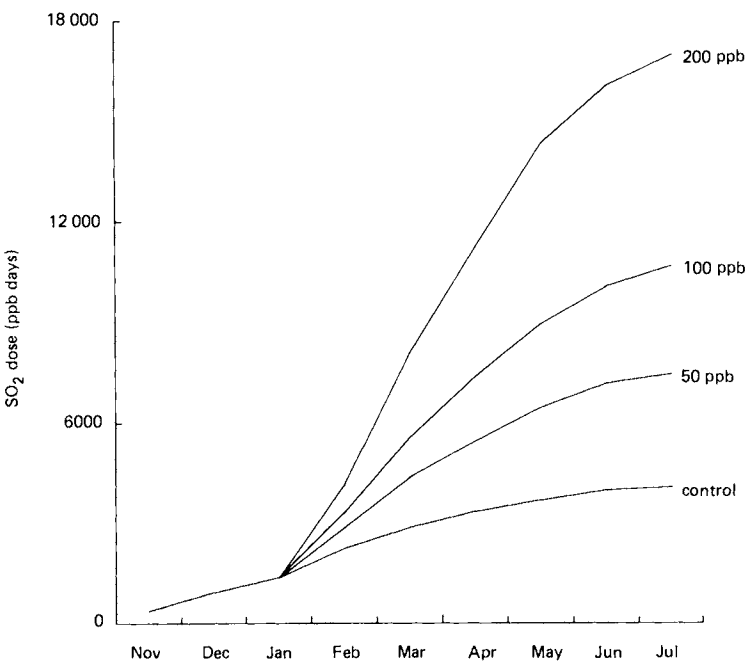


Figure 11.13 SO₂ accumulations for the three treatments and for the control (ambient) plots and growing season

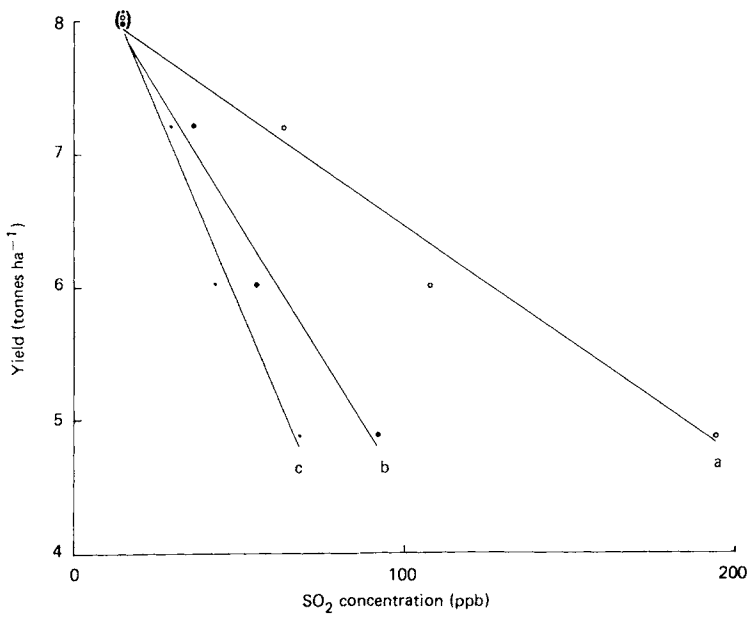


Figure 11.14 Variation of grain yield from the fumigated plots with average SO₂ concentration expressed as (a) the average concentration while actually fumigating, (b) the average concentration over the fumigation period, and (c) the average concentration over the growing season

7400 ppb days. The monthly dose accumulation is shown in *Figure 11.13*, where it should be noted that the dose was applied quite uniformly throughout February to June 1984.

Interpretation of crop results

It has been remarked previously (*Table 11.2*) that the effective SO₂ elevations may be considerably lower than the achieved fumigation elevations of 181, 91 and 47 ppb. On the premise that it is the long-term average concentrations that determine plant response (Garsed and Rutter, 1984), and not the frequency distribution or gaps in continuity, the average total concentrations through the growing season (6 November–8 July) could be as low as 69, 43 and 29 ppb. This analysis has important implications for the way in which crop results are interpreted. For example, a central result of the experiment, shown in *Figure 11.14*, is the effect of SO₂ concentration on barley yield. In 1983/84, increasing SO₂ concentrations were associated with falling yield. The upper line in *Figure 11.14* represents the trend of yield against the average total concentrations during fumigation. The slope is 0.17 tonnes ha⁻¹ per 10 ppb. For the centre line, the concentrations have been adjusted to the average values over the fumigation period, giving a slope of 0.40 tonnes ha⁻¹ per 10 ppb. Finally, the lower line shows the trend of yield with average SO₂ concentration over the whole growing season, giving a slope 0.58 tonnes ha⁻¹ per 10 ppb. The magnitude of this change (a more than three-fold increase in the yield reduction per unit SO₂ elevation) makes it imperative that the relation between yield reduction, average concentration and the manner of achieving it is properly quantified.

Acknowledgement

We should like to express our gratitude to the Department of the Environment and to the Ministry of Agriculture, Fisheries and Food for financing the greater part of this project, and to Dr M. Unsworth who conceived the original fumigation system.

References

- DE CORMIS, L., BONTE, J. and TISNE, A. (1975). Experimental method for the study of the effects on vegetation of sulphur dioxide applied continuously at sub-necrotic doses. *Pollution Atmosphérique*, **17**, 103–107
- GARSED, S.G. and RUTTER, A.J. (1984). The effects of fluctuating concentration of sulphur dioxide on the growth of *Pinus sylvestris* L. and *Picea sitchensis* (Bong.) Carr. *New Phytologist*, **97**, 175–195
- GREENWOOD, P., GREENHALGH, A., BAKER, C.K. and UNSWORTH, M.H. (1982). A computer-controlled system for exposing field crops to gaseous air pollutants. *Atmospheric Environment*, **16**, 2261–2266
- HALBWACHS, G. (1984). Organismal responses of higher plants to atmospheric pollutants: sulphur dioxide and fluoride. In *Air Pollution and Plant Life*. Ed. by Treshaw, M. p. 198. John Wiley, Chichester
- HEAGLE, A.S., BODY, D.E. and HECK, W.W. (1973). An open-top field chamber to

assess the impact of air pollution on plants. *Journal of Environmental Quality*, **2**, 365–368

KOZIOL, M.J. and WHATLEY, F.R. (Eds) (1984). *Gaseous Air Pollutants and Plant Metabolism*. Butterworths, London

LAUENROTH, W.K. and PRESTON, E.M. (1984). *The Effects of Sulphur Dioxide on a Grassland—A Case Study in the Northern Great Plains of the United States*. Springer-Verlag, New York

MCLEOD, A.R., ALEXANDER, K. and HATCHER, P. (1983). *A Prototype System for Open-air Fumigation of Agricultural Crops*. CEEB Report No. TPRD/L/2475/N83

ROBERTS, T.M. (1984). Long-term effects of sulphur dioxide on crops: an analysis of dose-response relations. *Philosophical Transactions of the Royal Society, London*, **B305**, 299–316

UNSWORTH, M.H. and ORMROD, D.P. (Eds) (1982). *Effects of Gaseous Pollutants in Agriculture and Horticulture*. Butterworths, London

THE USE OF COMPUTERS IN CANNING

D.J. STEELE

555 Chessington Road, West Ewell, Surrey, UK

Introduction

Throughout the food industry the basic manufacturing operations may contain the following elements (*Figure 12.1*): raw material receipt, ingredient preparation, blending, processing, storage, packaging and further storage prior to dispatch. All

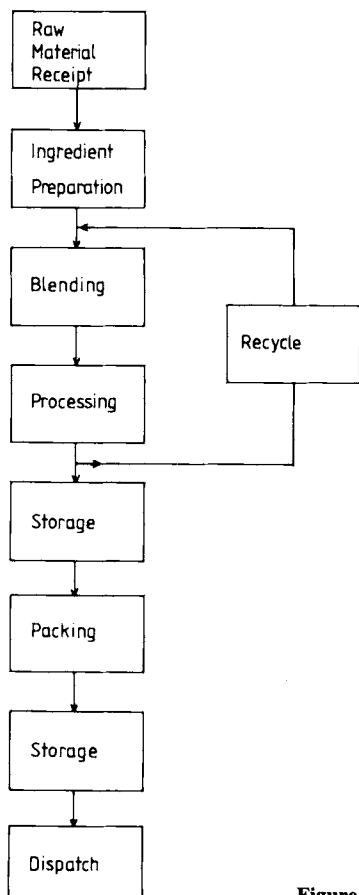


Figure 12.1 Elements of basic manufacturing operation

Table 12.1 UK PRODUCTION OF CANNED AND BOTTLED FRUIT AND VEGETABLES (TONNES) (DATA FROM MINISTRY OF AGRICULTURE, FISHERIES AND FOOD)

	<i>Total 1981</i>	<i>Total 1982</i>	<i>1983 Q1</i>	<i>1983 Q2</i>	<i>1983 Q3</i>	<i>1983 Q4</i>	<i>Total 1983</i>	<i>1984 Q1</i>
Fruit								
Strawberries	2277	2186	221	85	5174	0	5480	0
Raspberries	2917	4479	24	22	3664	0	3710	0
Plums	1269	5785	9	0	3998	2	4009	6
Rhubarb	4197	4581	0	6344	2145	0	8489	0
Prunes	6254	5473	1547	1871	1582	1038	6038	1432
Other Fruit Products	11 744	16 246	2819	3506	3731	4164	14 220	4101
Total	28 658	38 750	4620	11 828	20 294	5204	41 946	5539
Vegetables								
Baked Beans	359 643	379 988	102 319	110 088	74 237	97 165	383 809	101 496
Red Kidney Beans	2372	3232	1835	1879	1234	2243	7191	2955
Cut/Sliced Green Beans	8039	11 848	300	213	9037	77	9627	0
Garden Peas	56 582	53 775	3942	2574	49 497	367	56 380	1453
Processed Peas	130 101	131 804	41 459	48 343	22 063	32 553	144 418	35 181
Other Pulses	10 729	11 995	3547	2752	4747	2731	13 777	3240
Carrots	50 494	70 297	13 361	0	4241	38 481	56 083	9953
Mushrooms	4872	4408	2239	1402	938	1115	5694	926
Pasta Products	92 556	100 807	32 099	23 344	20 545	23 055	99 043	25 874
Potatoes	11 741	13 822	1413	1318	5636	133	8480	483
Vegetable Mixes	6528	6683	6431	197	196	2344	9168	4451
Other Vegetable Products	19 092	20 904	6783	3878	1835	4419	16 915	3867
Total	752 749	809 563	215 728	195 988	194 206	204 683	810 585	189 879

through this chain of operations there are applications for microelectronics and computer technology. Faced with increasing costs for labour, energy and raw materials, with little flexibility in selling price, food processors are now being forced to upgrade their processing operations in order to reduce costs. Despite the traditional image of the food industry lagging behind other industries in the use of advanced process control systems, this situation is at last now changing.

The purpose of this chapter is to show how this new technology can be applied to the cooking/sterilization and packaging of foodstuffs prior to storage. A wide variety of foodstuffs is prepared in this way (the UK production of canned foods and vegetables for 1983 amounted to about 800 000 tonnes; *Table 12.1*) and this therefore presents a sector of the industry where new technology can produce substantial economic savings as well as safety assurance in processing.

There is an important emphasis on public safety and processors must operate in strict compliance with certain regulations. Strict documentation and record keeping is required of all critical control points in the processing of each batch. With manually operated systems, and even those where traditional semi-automatic control systems are used, unscheduled process deviations can occur; operators can make mistakes and these may not be detected immediately. To obviate this problem, processors tend to operate with higher processing temperatures and longer processing times than required by specification. This can adversely affect product quality and production throughput and can result in unnecessary energy costs.

The validity of the sterilizing process is a problem which frequently confronts engineers and production and quality control staff. Methods of the measurement and control of a sterilizing process can now be improved significantly with the implementation of microprocessor technology. Validity can be assured, product safety and productivity can be measured and production costs reduced.

Cooking/sterilizing operation

For this operation the products are sealed in either metal containers (cans), jars, bottles or flexible pouches (Krishnappa *et al.*, 1982) and heated for a predetermined time at a predetermined temperature in a heating vessel (either a retort or similar apparatus; *Figure 12.2*). The basic flow chart for the sterilizing process after sealing the product in the container (Steele, 1980) is shown in *Figure 12.3*. The objective of the heat sterilization process is to destroy any harmful microorganisms that might be present in a preprocessed product, without degrading that product. Degradation may be identified as an unacceptable change in colour, flavour or texture of the foodstuff; the more severe the sterilization process, the more chance of degradation and, conversely, the longer the process the greater the production costs.

The scientific basis for the design of the heat sterilization process is the determination of the sterilization value, F_0 (a measure of the efficiency of the process), and allows comparisons to be made of the sterilizing effect carried out at differing temperatures. The general equation used is:

$$F_0 = \int_0^t \frac{T - T_r}{Z} dt$$

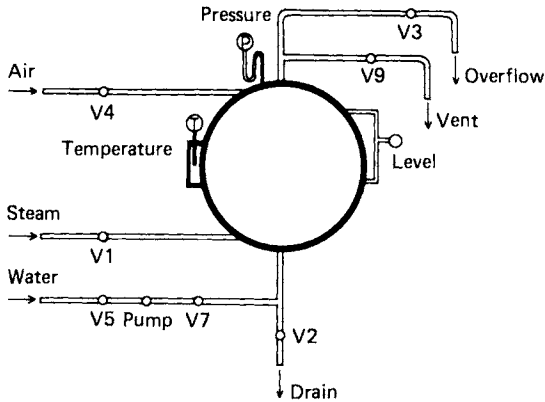


Figure 12.2 Schematic diagram of retort. V1, V2, etc. are valves

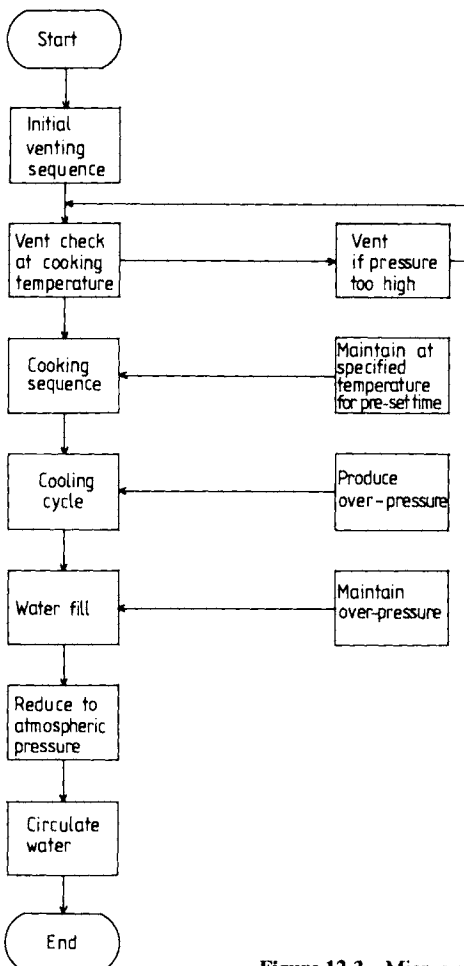


Figure 12.3 Microprocessor retort control : basic flow chart

where T_r is the reference temperature (normally 121.1°C), T is the processing temperature, Z is the basic parameter in the heat process evaluation, with units of temperature, and t is the time in minutes. A typical value for Z is 10°C for *Clostridium botulinum*. The F_0 value is determined by carrying out heat penetration measurements with a temperature-sensing element inserted into the product and located at the point of slowest heating. The process also requires that the integrity of the container be maintained to minimize the possibility of postprocess contamination. Therefore, during both the cooking and cooling stages of the process, an external pressure must be maintained to ensure that the differential pressure on the container is minimized. This is to prevent buckling or straining of can seams.

Microcomputers applied to retort control

The Leatherhead Food Research Association recognized, as early as 1975, the potential use of microcomputers for process control in the food industry in providing more efficient, safe and reproducible process conditions. To demonstrate this potential within the food industry a microcomputing system was purchased (Motorola 6800) and a dedicated system was designed and constructed to operate a small rotary retort within the pilot plant area of the laboratories (Neill and Steele, 1979).

In essence, a retorting process consists of a sequence of operations, namely:

1. Water supply and air supply check;
2. Venting and steam supply check;
3. Heating to the cooking temperature, with a venting check to ensure all the air in the vessel is expelled;
4. Maintaining the cooking temperature for the cooking time;
5. Producing and controlling an over-pressure;
6. Filling the retort with water, maintaining the correct pressure;
7. Cooling—circulating water through the retort;
8. Emptying the retort.

Following successful demonstrations, and after gaining useful experience, the system was used in cooperative trials with a Member to control a factory production retort (Frazer–Millwall Rotary) (Steele, Neill and Ireland, 1982). The trials demonstrated the technical viability and reliability of using a dedicated system for this purpose.

Commercial computer systems have now been developed, or adapted, specifically for the control of a sterilization process. Two basic methods have been adopted: direct and derived value control.

DIRECT CONTROL

The philosophy of Neill and Steele was to use the computer: (1) to control the processing temperature and time within close limits; (2) to control the pressure within the retort to prescribed values during the cooling stage; and (3) to monitor selected centre can temperatures during processing, and compute and display the progressive F_0 values.

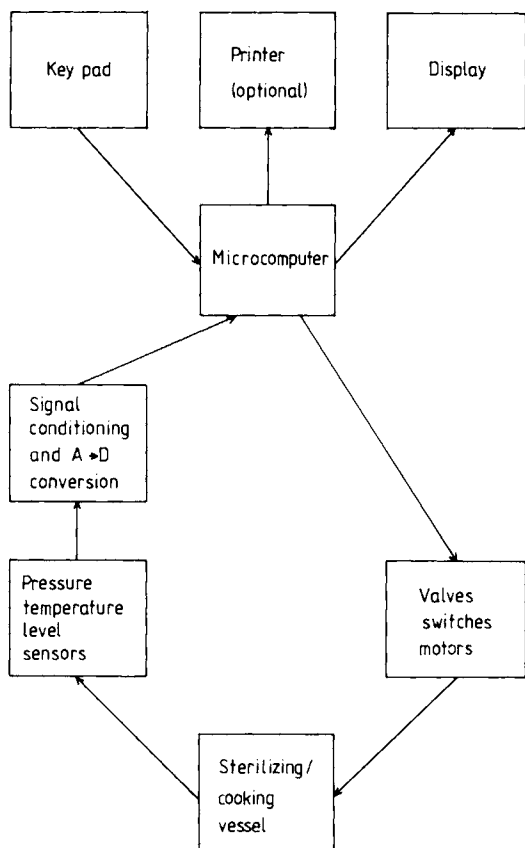


Figure 12.4 Schematic representation of computer-based control system

The retort input and output services (i.e. steam, air and water) were controlled using on/off solenoid valves. The retort temperature and pressure were measured using a platinum resistance thermometer and a strain gauge diaphragm pressure transducer, respectively. Three thermistor probes were used to measure product temperatures in selected cans to enable F_0 values to be computed and displayed. The water level in the retort was sensed by conductive probes (*Figure 12.4*). The operator was able to communicate with the control system by means of a touch keyboard. Initially, the operator was able to enter set points (e.g. cooking time and temperature) but it was found to be more reliable for the operator to enter a code number for a particular product and for the computer to select automatically the various set points from a preprogrammed memory. An alpha-numeric display enabled the code number to be verified and the processing temperature, pressure, time and status conditions (i.e. the current stage of the process) to be displayed. A mimic display also indicated the status of the solenoid valves of the retort.

Both anticipatory and time-proportional modes of control were used (under software control) to maintain the retort temperature to $\pm 0.2^\circ\text{C}$ during the cooking cycle.

The retort action under computer control is as follows.

1. The operator switches on the control unit and enters his pass code and product code.
2. The operator is informed by the display that these have been accepted and is instructed to proceed.
3. When the RUN key is pressed, the following sequences are followed.
 - i. Water supply and air supply check: With the overflow and drain valves open, water is pumped into the retort for 15 s and a pressure reading taken. The overflow valve is then closed, the air valve opened and a further pressure reading taken. Correct values indicate water and air services are available; if not, a warning is given.
 - ii. Venting: The drain, vent, overflow and steam valves are opened and the retort temperature monitored; a correct reading indicates the presence of steam. Venting proceeds for 3–5 min.
 - iii. Come up: Only the steam valve is opened. When the temperature reaches the cooking temperature the steam valve closes. The pressure and temperature are automatically checked against theoretical values stored in the computer memory; if the values are correct, the process continues; if not, a further venting cycle is initiated.
 - iv. Cooking: The temperature is controlled closely for the set cook time, and the rotation cycle controlled during this time.
 - v. Over-pressure: At the end of the cooking cycle all valves close and the pressure in the retort is measured. The microprocessor adds to this pressure the value of the specified over-pressure. This total pressure is then achieved by opening the air valve.
 - vi. Filling: The water valves are opened and the pump switched on. The pressure in the retort is maintained at the correct value using the air and vent valves. The level detector provides a signal when the retort is full of water. When this happens only the vent valve is opened and the water pump is switched off, allowing the pressure to fall slowly to atmospheric pressure.
 - vii. Cooling: water is pumped into the retort and is allowed out through the overflow valve for the preset cooling time.
 - viii. The drain valve opens and the pressure in the retort is increased to force the water out. When the retort is empty of water the message FINISHED is displayed, the drain, vent and overflow valves are opened, and the retort is safe to open.

For similar retort loads and processing conditions the temperature and pressure records of successive runs were found to be identical. Variations about the set cooking temperature were $\pm 0.2^{\circ}\text{C}$ while pressure fluctuations during this period were reduced to ± 0.5 psi.

During the filling cycle, pressure variations were found to be only ± 0.1 psi, gradually increasing to ± 0.6 psi at the point where the retort was full of water. Under manual or semi-automatic control, this part of the processing cycle is difficult to control and often results in large pressure variations, causing peaking of the cans and possible damage to the seams. During the 9-month period of factory operation, the unit quickly became adopted as the standard operating procedure by the operators. The advantages of this system were found to be reproducibility of performance over many operating cycles, consistency of operation and saving in operator time. The retort could be left to run without requiring any attention. In the event of an abort occurring, information on the status of the retort at the time

of the abort could be readily obtained by the operator. A further improvement was the increased accuracy to which F_0 values could be obtained.

Further trials were also successfully carried out on the same production retort using a Texas PM 550 programmable controller (Richards and Steele, 1982) to emulate the control program developed using the dedicated control system. Similar results were obtained. Two advantages over the dedicated system were: (1) alterations to plant in the factory and the wiring of the control programs and checking of the system could be done at convenient times before installation, so that production was not disturbed; and (2) program changes on plant could be easily and quickly effected with minimum disturbance to production.

DERIVED VALUE CONTROL

Tiexeira and Manson (1982, 1983) have adopted an alternative approach using derived value control, i.e. accepting that deviations of processing parameters can and do occur and correcting for these deviations using a mathematical model of the kinetics of heat transfer within a canned product. The aim is to dispense with centre can temperature measurements during processing. The model is based on first-order reaction kinetics (describing the thermal inactivation of bacterial spores), coupled with a numerical solution of the two-dimensional unsteady state heat conduction for a finite cylinder.

The mathematical expressions which describe the temperature distribution pattern over time (heating from the surface) are given by Tiexeira *et al.* (1969) as:

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial h^2} \right)$$

and

$$\alpha = \frac{0.398}{\left(\frac{1}{R^2} + \frac{0.427}{H^2} \right) f_h}$$

where t = time; r = radial position in cylinder; h = vertical position in cylinder; α = thermal diffusivity of can contents; R = can radius; H = $\frac{1}{2}$ can height; and f_h = slope of heat penetration curve.

The computer model was developed from this expression, was verified experimentally and formed an integral part of the control logic used in a microcomputer control system. The operator is required to feed specific input data from predetermined physical measurements and visual inspection of the product to be loaded into the retort (for example, product, can size, initial product temperature, viscosity, fill weight and pH, as well as other factors critical to heat penetration).

During the process cycle, the retort temperature is monitored at regular intervals and compared to the established value specified for that point in the retorting cycle (Figure 12.5). If there is agreement the computer calculates the temperature reached at the can centre over that time period and the resulting sterilization value achieved. Should any deviation occur and the actual temperature does not agree with that specified, the computer model is used. The model simulates completion of the process based on the actual temperature reading and predicts the final F_0 value

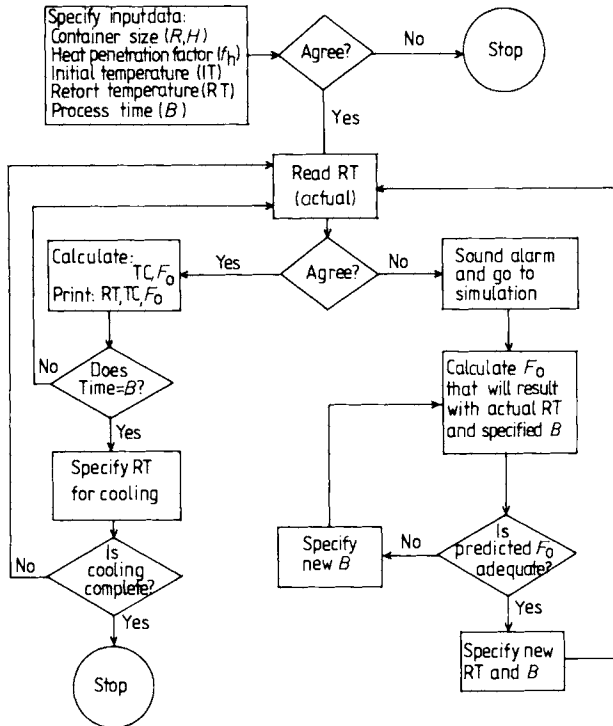


Figure 12.5 Control logic for on-line correction of process deviations

that would result. If this F_0 value is not adequate, the computer specifies a new process time to be used at this measured temperature (which becomes the new specified temperature). The control carries on as before until a process deviation requires an update.

When the specified process time has been reached and cooling begins, the control logic calls for the computer to specify the new retort temperature established for the cooling cycle. The computer continues to read, compare and calculate at each time interval until cooling is complete and the entire process cycle is over.

This approach requires that the physical properties which govern heat penetration be controlled carefully so that the product heats at the same rate as the model has been programmed to simulate. It also assumes that the position used to measure the retort temperature represents the temperature throughout the retort and that all the air has been vented.

Brown (1982) has described the current research investigating this modelling approach to sterilization. Variables under consideration are:

Processing variables

- Processing temperature and time
- Cooking temperature and time
- Initial product temperature
- Cooling temperature gradients
- Cooling water temperature
- Flow rate

Product variables

Can geometry
 Product thermal diffusivity
 Packing density
 Heat penetration characteristics

Also under consideration is the way in which changes of other cooking parameters influence process efficiency. For example, there may be trade-offs between flavour retention, nutritional retention, textural quality, energy input and production rate, assuming the minimum requirements for product sterility have been met. A MACSYM 2 microcomputer-based control system, in conjunction with a production vertical retort and pilot scale rotary retort, is used to develop the technique of derived value control. The multi-tasking capabilities of the computer allow interactive multi-term control loops and machine sequence control programs to be developed, enabling the effects of individual control algorithm components and variables to be investigated.

Kleiman and Wertman (1980) describe a commercially marketed computer which computes and controls the process cycle based on measurements within the retort (*Figure 12.6*). Process optimization is achieved using mathematical and

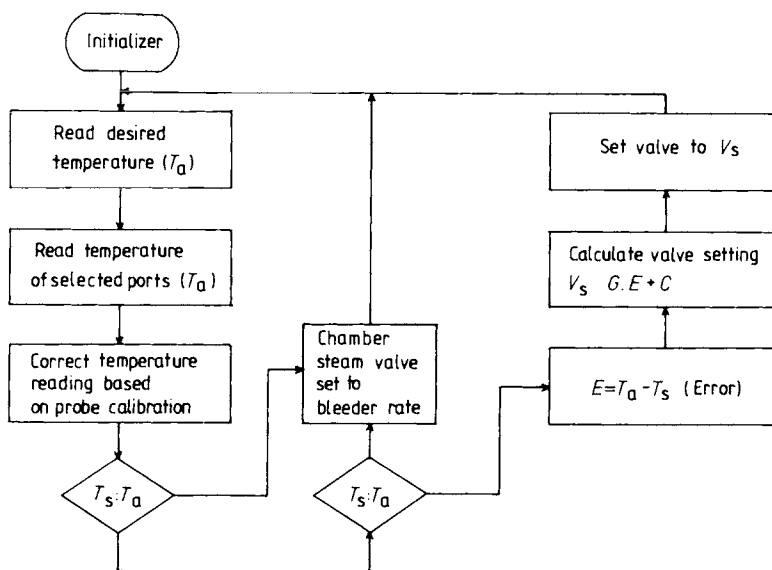


Figure 12.6 Microcomputer internal program for temperature control, showing decision-making and mathematical/computation capabilities

statistical software. It is claimed that the computer automatically corrects for: deviations from probe standards entered into the program, process time and temperature, desired F_0 value, and type of cooking cycle. The computer controls start up by a fail-safe interactive program, runs the actual cycle (including automatic venting) and calculates F_0 on-line. The computer also monitors the cycle, stores data for later retrieval and performs heat distribution studies, rate of change and statistical studies.

Levy and Havacek (1980) described their experiences using a custom-designed computer in the canning of shrimps. The main components of the system are a dedicated computer, video display unit, keyboard terminal, printer and monitoring unit. The computer monitors the retort temperature once per second and maintains the process temperature by positioning the steam control valve. If the temperature drops below the set point, the process cycle is automatically extended in direct relation to the extent of the deviation. Three retorts are monitored and controlled simultaneously using one computer. An operator's console is placed adjacent to the retorts, with the computer and print-out facilities in an office in an adjacent building. The console includes a visual display unit to display process conditions and any alarms. It is claimed that by using computer control, product quality has been improved and that process times have been reduced by 30–35%. This has resulted in improved plant efficiency, increasing the output and productivity by approximately 20%.

Future trends

The performance of process control systems will continue to improve, the impetus coming primarily from the demand for more process-oriented functions.

The increasing use of microcomputers will result in new sensors and final control elements. These will have built-in error monitoring, corrections for non-linear characteristics and automatic recalibration facilities.

Control strategies and algorithms will be developed and implemented for multi-variable control (Brook, 1981). Control of the process will probably be based on several related parameters that are closely interdependent. Single-loop controllers will offer a wide choice of functions, including self-tuning and adaptive algorithms.

In the future there will be more scope for distributed control methods in food industry processes (King and Hunt, 1980). In these schemes the control function will be implemented at each unit process or section of production line on an individual basis (each using its own microcomputer). This will offer greater reliability and operator acceptability than control systems, plus the ability to install control systems in stages.

Individual local control units will be connected together using data transmission lines to a central station for overall unit control, coordination and process monitoring purposes. Thus, the sterilization process will form but part of an integrated structure for factory processing. On the processing side we will see significantly more supervisory and management functions, resulting from virtually unlimited data storage capabilities. Better information systems will be possible, allowing a greater range of information processing for production control and management.

Conclusions

It has been demonstrated that microcomputer control of a sterilization process can give reproducibility and consistency of performance over many operating cycles. The process can be left to run with the minimum of attention; providing a saving in operator time. Sterilization values can be computed and controlled to a better

accuracy than by previous methods. In general, the first benefit to be derived from the use of computers in automatic operation of retorts for the sterilization of food materials, is more precise control enforcement (Getchell, 1980). This results in the assurance of repeatable process cycles, optimization of the process, reduced process times, increased product safety, increased output and productivity (up to 20% has been reported) and reduced production costs.

The second benefit is that of operational information (from the continuous checking of process parameters, services and actuators) and display of this information in a concise form for the operators and supervisors. Alarm conditions can be flashed to the operator detailing the exact nature of the problem. At the supervisor level, information can show total productivity for the entire cook-room area.

The third general benefit is the virtually unlimited documentation capability of the system. All variables throughout a process can be stored; for example, dates, product identification number, batch numbers, operator, process times, temperatures, alarm conditions, F_0 values. This is ideal for administrative purposes where the information can be recalled and formatted to comply with regulations and the requirements of quality control departments. Management reports may be as simple or as complex as desired.

Although all these benefits have been demonstrated, there is still a reluctance by some food processing companies to make full use of this new technology. This may be due to lack of knowledge at higher and middle management, lack of in-house skills, an unwillingness to change traditional methods, or the inability to quantify financial savings from a paper study. How, for example, does one put a price on better quality or increased safety?

It is expected that further benefits will be realized once this technology has been used and accepted. Further developments should permit application to other control functions. For example: scheduling retorts to optimize steam usage and reduce boiler requirements would reduce fuel requirements and costs; monitoring utilities such as steam header pressures, cooling water temperatures and pressures would enable automatic compensation for any deviation of the required value; and automatic calibration of, and corrections for, variabilities in sensor characteristics would reduce problems of measurement error.

Although the emphasis has been on process control of the sterilization stage, in order to realize the full potential of the computer the integration of the complete process must be considered: for example, control of can filling level, product viscosity, compensation for changes in precooking temperature, the validity of seals before and after sterilization, coding and packing for dispatch. There is also much that can be done to allow for the temperature distribution within retorts during processing and to use control to ensure that the different 'zones' are at the required temperature. With the rapid developments taking place in microelectronics and computing there is an exciting future for process control in the food industry.

References

- BROOK, R.C. (1981). Use of microcomputers for process control. *Food Technology*, **35**, 89–91
- BROWN, G. (1982). Application of microcomputer technologies in the food and allied industries. *Measurement and Control*, **15**, 409–412

- GETCHELL, J.R. (1980). 'Computer process control of retorts.' American Society of Agricultural Engineers Paper No. 80-6511
- KING, P.J. and HUNT, J.A. (1980). *The Application of Microprocessors for Control In The Food Industry*. Warren Spring Laboratory, Stevenage
- KLEIMAN, L.A. and WERTMAN, L. (1980). Computer control for retorts. *Food Engineering*, **10**, 73-74
- KRISHNAPPA, K.G., SRIVATSA, A.N., GHACH, K.G., EAPON, K.C. and VIJAGANAGHAVAN, P.K. (1982). Heat processing of foods in flexible pouches—development and future in India. *Indian Food Packer*, July–August, 11-17
- LEVY, C. and HAVACEK, R.G. (1980). Computer control optimizes retort cook for yield, quality, safety. *Food Processing*, **10**, 74-77
- NEILL, R.D. and STEELE, D.J. (1979). 'Microprocessor applications in control of food manufacturing processes—retort control.' Leatherhead, Food Research Association Research Report No. 307 (August)
- RICHARDS, P.A. and STEELE, D.S. (1982). 'An Evaluation of the Texas Instruments PM 550 Programmable Controller.' Food Research Association Research Report No. 389
- STEELE, D.J. (1980) Applied microprocessor controls to retort. *Food Engineering International*, **12**, 28-32
- STEELE, D.J., NEILL, R.D. and IRELAND, E.B. (1982). 'Factory trials using a microcomputer to control a production retort.' Leatherhead, Food Research Association Research Report, No. 381
- TIEXEIRA, A.A., DIXON, J.R., ZAHRADNILS, J.W. and ZINSMASER, G.E. (1969). Computer optimisation of nutrient retention in thermal processing of conduction heated food. *Food Technology*, **23**, 137
- TIEXEIRA, A.A. and MANSON, J.E. (1982). Computer control of batch retort operations with on-line corrections of process deviations. *Food Technology*, **36**, 85-90
- TIEXEIRA, A.A. and MANSON, J.E. (1983). Thermal process control for aseptic processing systems. *Food Technology*, **37**, 128-133

COMPUTER CONTROL OF THE ENVIRONMENT IN ANIMAL HOUSING

J.J. LEONARD and J.B. McQUITTY
University of Alberta, Edmonton, Canada

Introduction

The fact that computer control of the environment in animal housing is a topic for discussion, let alone implementation, is the result of the convergence of a number of separate trends. These trends include the increasing intensity of confinement housing operations, the growing awareness of animal welfare, increasing evidence of the effects of the environment on animal production and the advent of cheap, robust microelectronic components.

High capital costs of land, buildings and equipment have driven producers to increase the stocking density within buildings. Animals that are housed in such buildings generally are not at liberty to seek their own preferred environment and, consequently, high levels of management are required to ensure that a suitable environment is provided for them. The economics of the process sometimes have led to conditions which, while optimizing return on investment, have been perceived as being detrimental to animal health and welfare. These perceptions, as well as the desire to optimize productivity, have led to the need to describe and to define more precisely the optimum animal environment. Much work is required in this area but it is apparent that the animal environment is a complex of many factors and that control of all these at optimum levels will be a complicated task.

As well as being composed of many factors, the environment in animal housing is subjected continually to disturbing forces. Thus, the condition of ventilation air varies diurnally and seasonally, as well as in accordance with weather patterns. In addition, the activity and metabolism of the animals are influenced by factors such as feeding and lighting regimes. Consequently, in order to counteract these disturbing influences, continual monitoring and adjustment of heating and ventilation rates are required. Even if only one component of the environment (e.g. temperature) is monitored, this control is achieved best by a machine rather than a human operator. As more and more components are monitored, the control task demands the ability to handle more information and to make complex decisions on the basis of this information. A simple thermostat is no longer adequate and the task is more suited to a computer.

While such control tasks are common in other fields such as the aerospace and chemical industries, the computers used to carry out these tasks were too expensive to be applied to most agricultural situations until fairly recently. The advent of

large-scale integrated circuits and the microprocessor, however, has made computer control of animal housing affordable and realistic.

This chapter attempts to review the problem of environment control in animal housing and to examine the applicability of the computer to this problem. The nature and requirements of a computer-based control system are described and some of the features of such systems are discussed with reference to the experiences of ourselves and others.

The animal housing environment

The environmental complex has been described by Baxter (1969) as being comprised of social, structural and climatic constituents, each of which interacts with others. Recognition of these interactions is vital in the design of animal housing but, for convenience, this chapter will concern itself primarily with the climatic constituents of the animal environment. These are summarized in *Figure 13.1* and may be divided into thermal and non-thermal variables.

The thermal variables are those that affect the thermal equilibrium of the housed animal and include air temperature, velocity and relative humidity and radiant heat transfer. The non-thermal variables are those which affect 'air quality' and, therefore, pose at least a potential threat to animal health. These include concentrations of gases such as carbon dioxide (CO_2), ammonia (NH_3), methane (CH_4) and hydrogen sulphide (H_2S). In addition, another variable of concern is the concentration of aerosols composed of dust particles and viable materials such as bacteria, viruses and spores. Since particles of less than $5\mu\text{m}$ diameter are more

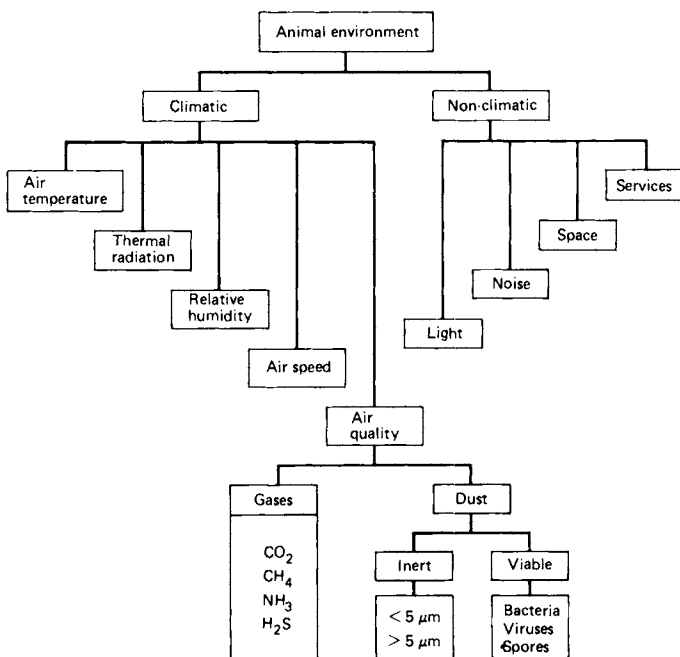


Figure 13.1 The animal environment

likely to be inhaled into the lungs (Wathes, Jones and Webster, 1983) and thereby predispose animals to respiratory disorders, these are considered separately from larger particles which are intercepted in the upper respiratory tract.

Perhaps because thermal parameters are easier to measure, much more is known about their optimum and limiting levels than those of the non-thermal quantities. Their effect on the critical temperature and growth of pigs is well documented by Close (1981) and has been modelled mathematically by Bruce (1981). Similarly, the temperature requirements for poultry have been well researched and are reported by authors such as Reece (1982) and Charles (1981). Ruminants are generally not housed on a year-round basis and they adapt better to cold temperatures (Young and Deegan, 1981); consequently, their production is seldom limited by thermal factors (Webster, 1981; Brugger, 1982).

The effects of the non-thermal environment on animal production and health are not as well documented as those of the thermal. Indeed, relatively little is known about the normally occurring concentrations of air contaminants within confined livestock operations, and much work remains to be done on the short-term and chronic effects of these contaminants at various concentrations on animal well-being.

With respect to the pollutant gases mentioned above, Wathes, Jones and Webster (1983) have pointed out that, whereas occupational health standards have been established for humans, such figures are not available for farm animals. Wathes, Jones and Webster recommend the use of 'safe' limits proposed by Bruce (1981) of 5, 20, 300 and 3000 ppm for H_2S , NH_3 , CH_4 and CO_2 , respectively. Honey and McQuitty (1976) reviewed the effects of aerosol particles on animals and the concentrations of these particles that had been found in animal housing. The effects of both inert dust and microbial particles on animal health have not been investigated fully (Wathes, Jones and Webster, 1983) but there are sufficient indications to suggest that excessive concentrations of particles in the air adversely affect the respiratory health of housed animals.

Recent studies involving monitoring of environments in animal housing under commercial conditions (Glennon, McQuitty and Clark, 1984; Leonard, Feddes and McQuitty, 1984; McQuitty, Feddes and Leonard, 1984) have indicated that air quality should give cause for concern in animal housing. Although concentrations of contaminant gases were generally low in these studies, situations did arise where concentrations of, for instance, NH_3 were high enough to pose a threat to the health of human operators. In addition, dust concentrations, which varied with animal activity, were generally high. The long-term effects of continued exposure to such concentrations of contaminants have not been researched sufficiently, and should not be neglected.

The quality of the climatic environment in animal housing is controlled by ventilation and, if necessary, the addition of supplementary heat. The ventilation process, which results in the dilution of contaminants, conventionally is controlled above some predetermined minimum rate on the basis of temperature only. This may have the fortuitous result of adequate control of the non-thermal components of the environment but, for continuous optimum control of the total environment, two requirements are outstanding. The first requirement is the previously mentioned need for more information on limiting and optimum concentrations of contaminants. Assuming that the first requirement can be met, the second requirement is for more sophisticated control systems that are capable of monitoring the total environment instead of one component only.

Control systems

The term 'control system' usually implies a closed loop such as that represented in *Figure 13.2*. This figure depicts a barn temperature control system which operates as described below.

The output from a temperature sensor, which is usually an electrical signal, is conditioned so that it is compatible with the rest of the system. The conditioned signal is then compared with a value corresponding to the desired temperature (i.e. the 'set point'). The difference between the sensed and set-point values is the error signal which is transmitted to the controller.

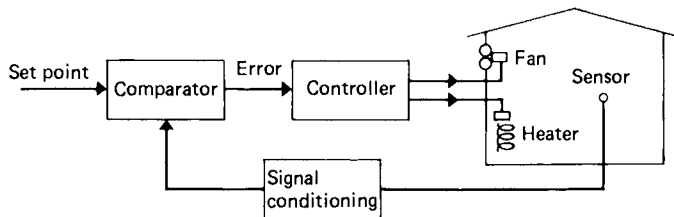


Figure 13.2 A typical feedback control system

The objective of the controller is to minimize the magnitude of the error signal by initiating changes in the controlled equipment, in this example the fans and heaters installed in the barn. However, there is an almost infinite number of strategies that the controller could pursue in turning heaters and fans on and off. With on/off control the controller simply turns the fans or heaters on or off in response to the sign of the error signal. This type of control is common in thermostat systems and can produce overshooting and instability problems if the temperature sensors respond too slowly to changes in air temperature.

In general, the stability of a control system depends on the speeds of response to change of the components of the system. If sensors respond too rapidly, the system will always be attempting to correct for minor local fluctuations about the set point when the overall environment is quite satisfactory. Too slow a response from sensors will result in the control system continually trying to 'catch up' with the barn. A useful parameter in this regard is that of the time constant, which is defined as the time required for a component of the system to reach 63.2% of its final value after a step change. Clark and Cena (1981) have given a good account of the effect of sensor time constants on control performance and showed that the ratio of sensor time constant to the period of fluctuations in the quantity being sensed should be less than 0.025 to give an indication within 1% of the true value of the quantity.

Proportional control can give greater stability than on/off control, by initiating control actions that are proportional to the error signal. Thus, fan speed, the number of fans operating, or the time that fans are operating in a given control period could be varied in proportion to temperature excess above the set point. Just as proportional control implies action proportional to the error signal, so derivative and integral controls imply action proportional to the rate of change of the error signal and to the sum of the error signal over time, respectively. Derivative control cannot be used by itself since it does not respond to a constant error and, in fact, proportional, integral and derivative control are often used concurrently in what are called PID controllers.

The adoption of a given type of controller is usually on the basis of cost, control precision and stability. The widespread use of the above types of controller in industry may be explained by the fact that they are implemented easily using analogue electronics. Consequently, they have proven reliability and performance characteristics that are well understood. For instance, the application of conventional control systems theory to animal housing has been explained by Cole (1980). The performance of these controllers, however, is duplicated readily using computer techniques and, in addition, the computer has allowed variations of these controllers and more complex strategies to be implemented in a cost-effective manner.

Examples of more complex systems are those using adaptive and feed-forward control techniques. As the name implies, adaptive control systems continuously 'learn' about characteristics, such as response times, of the controlled process and adapt to changes. Feed-forward control, on the other hand, anticipates changes in the process due to external disturbances. Thus, in the case of a barn, the effect of a change in outside temperature or humidity could be anticipated, and corrective action initiated, before it caused a change in the environment inside the barn.

Conventional and computer-based systems

Conventional systems for the control of the environment in animal housing vary in complexity, depending on the scale of the enterprise and the variations in climate that have to be countered. In the least complex systems, all the components in *Figure 13.2*, except for the barn, fans and heaters, are embodied in a human operator. Sensing of conditions in the barn is done subjectively and the operator turns on fans and heaters, or opens and closes ventilation openings, as he perceives the requirement. If the operator is skilled and experienced, such a system can result in quite acceptable performance, provided that the conditions in the barn do not vary rapidly or unpredictably. An obvious improvement to this system would be the provision of temperature and humidity indicators in the barn but, even then, the high requirements for skilled labour, coupled with the inherent discontinuity in monitoring, makes such systems unattractive for any but the smaller enterprises. Nevertheless, even in large-scale operations, the ability of a stockman to assess subjectively the quality of the environment should not be discounted.

The limitations of human operators have created the need for continuous, automatic environment control and, although humidistats are used occasionally, this generally is achieved on the basis of temperature through the use of thermostats. Essentially, these are temperature-controlled switches and, therefore, are applied most easily to on/off control systems. However, they can be set so that, for instance, individual ventilation fans are turned on at progressively higher temperatures to give a form of 'stepped' proportional control. In systems where heaters and fans are operated with separate thermostats, the control circuits must be interlinked in some way to prevent the effect of the heaters causing excess ventilation and energy wastage. Furthermore, ventilation inlets should be controlled so that air velocities are maintained at sufficient levels to promote adequate mixing and distribution of the inlet air at all ventilation rates. In some systems, this supposedly is achieved by using pressure differential across the inlets as the basis for controlling inlet area.

Thus, even if temperature is to be the only environmental variable that is controlled directly, a large installation can require numerous thermostats, some of which must be interlinked, and all of which must be set carefully to ensure the desired performance of the system. The actual performance of such systems is seldom checked on more than a daily basis, although alarms are required in case of system failure. In addition, the flexibility to implement different control strategies is limited within such systems and is determined primarily by the initial system design. Nevertheless, bearing in mind these limitations, thermostat control systems can provide satisfactory and reliable temperature control. In modern intensive animal production, however, good temperature control may not constitute adequate environment control and computer technology is available that could satisfy the increased demands of more general environment control and, at the same time, provide information on system performance.

The microcomputer, whether it be a single-chip controller or a desk-top unit with a keyboard and monitor, is essentially a very good processor of data. The fact that these machines are readily and economically available means that a vast, and hitherto unavailable, array of opportunities has opened up in the control of animal environments. From a data processing point of view, one machine can easily integrate the control of fans, heaters and inlets, change set-point temperatures automatically on a diurnal or longer-term basis, control lighting regimes, include humidity, gas and dust concentrations in control strategies, print out or display a record of environment measurements, and initiate alarm actions that could include telephoning an operator. In addition, the computer could be reprogrammed to implement different control schemes without any changes in the hardware of the system.

Unfortunately, however, the data processing power of modern computers has outstripped developments in other areas. Since a system is only as strong as its weakest component, a typical computer-based control system will now be analysed to identify where advances are required in equipment or knowledge before the full potential of the computer can be applied to the animal environment.

A computer-based system

Figure 13.3 shows the components of a simple control system based on a microcomputer. As with the system shown in *Figure 13.2*, the operation of a computer-based system depends initially on the sensors and signal-conditioning circuitry. The sensors must provide accurate information on the controlled variable and be capable of maintaining accuracy for extended periods in the barn environment. Barn environments are often characterized by high humidity and/or high dust levels, which are both enemies of electronic circuitry. Whereas the other components of the system may be housed in more suitable conditions, the sensors may have to be situated in the barn. They should be designed, therefore, to withstand the environment and should be located so as to avoid damage by stock and equipment, yet give a good indication of the conditions in the animal microclimate. These requirements may be difficult to fulfil and may require preliminary monitoring of the barn or the use of multiple sensors to overcome variations in the controlled variable (e.g. temperature) within the controlled space.

Although temperature sensors, such as thermistors, having proven reliability and suitable time constants are available, the same cannot be said about sensors for the

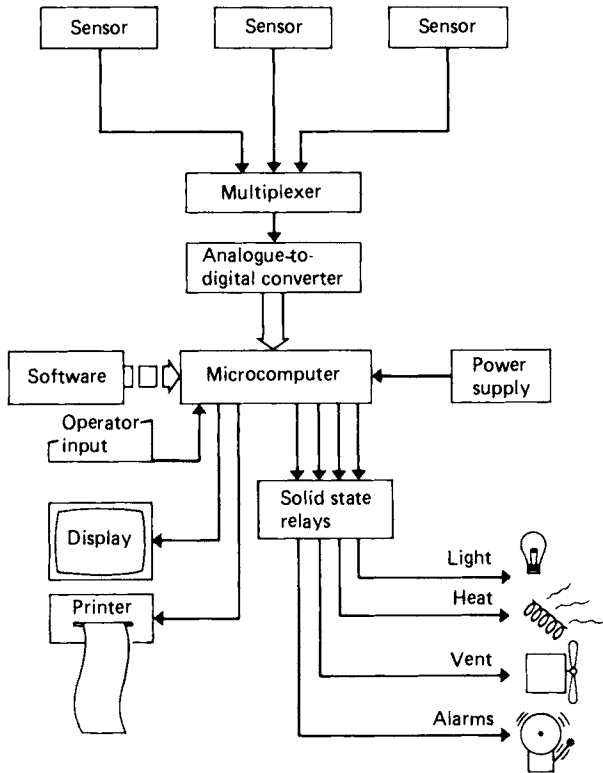


Figure 13.3 A microcomputer-based control system

other environmental variables, with the possible exception of humidity. Research-quality instruments are available for measuring gas and particle concentrations, but these are generally too expensive to be incorporated into a farmer-operated control system. Control of the environment that is based on more than temperature and humidity will not become a practical reality until cheaper, reliable sensors are developed for the other environmental factors.

Signal-conditioning circuitry is required to convert the output from the sensors to voltage signals that are reasonably free of electrical noise, and of a magnitude that is compatible with succeeding stages of the system. Most animal houses contain conveyors and other equipment driven by electric motors. These and other farmstead equipment can act as sources of electrical noise, and shielding of sensor cables may be required if the noise is excessive and cannot be filtered out of the signal by the signal-conditioning circuitry. Another function of the conditioning circuitry is to amplify the sensor signal, if required, to a magnitude suitable for further processing.

The conditioned sensor signals then are fed to a multiplexer, which is an electronic selector switch controlled by the computer. Once a sensor input is selected, it is directed to an analogue-to-digital converter (ADC), which converts the sensor voltage at that instant to a binary digital value. Unlike a chart recorder, the computer takes 'snap shots' of the sensor outputs at discrete times rather than continuously monitoring sensor outputs. The resolution of the ADC depends on the number of bits (binary digits) in its output. Thus, 8-bit and 12-bit converters

offer resolutions of 1/256 and 1/4096 of full scale, respectively, and, if input voltages range between 0 and 10 V, the finest resolutions that can be obtained are 0.039 V and 0.0024 V, respectively. Although unlikely to present a problem in environmental control systems, the analogue-to-digital conversion process also takes a finite time. The conversion speed governs the maximum frequency at which outputs can be sampled, and this sampling frequency should be high enough to obtain a true indication of the sensed variable. Having been converted to a digital format, the sensor information is now available to the computer.

The computer typically consists of a central processing unit, memory, devices for handling input and output of data and a clock or timing device. For environmental control, the central processing unit will be some form of microprocessor and, in the applications considered here, the whole computer will consist of a number of electronic components and chips mounted on a single card. In fact, the whole computer together with multiplexer and ADC could occupy a single chip. Such compact packaging has the advantage that protection from hostile environments is easier than for larger machines. The use of desk-top or 'personal' microcomputers in such control applications is quite possible but unlikely, except for those cases involving hobbyists, researchers, or where a desk-top machine is 'networked' to manage or obtain data from a number of smaller controllers. In any event, for the computer to operate, it must be supplied with power and a program (software). Both of these requirements merit discussion at this point.

Because of their remoteness from distribution stations and the frequent presence of electric motors and other equipment in the vicinity, rural power supplies are notorious for irregularities in line voltage, variously referred to as spikes, surges and sags. These, together with outright power interruptions, pose severe threats to the integrity of computer-based control systems that are required to operate continuously. Consequently, a power supply is required that offers both over-voltage protection and automatic switching to a battery back-up if line voltage drops. In the event of a total power failure, the system must be designed to be fail-safe by making provision for sufficient ventilation in such a case.

The software with which the computer is programmed is, of course, of critical importance. It controls the overall operation of the system but can be divided functionally into three sections. The first task of the program is to control the acquisition of data from the sensors and, if required, to convert the raw voltages into meaningful units for recording or display purposes. Consideration must be given here to the number and types of sensors and to sampling rates or intervals. Different structures will respond at different rates to external changes and these must be taken into account, together with sensor time constants, in deciding how frequently to sample the conditions in the environment and how frequently to exercise control actions. A discussion of this problem as it relates to temperature control has been given by Clark and Cena (1981).

The next and central task of the software is to implement a control strategy or algorithm. Since the computer embodies a clock, the control function could be as simple as turning lights on and off at specified times. However, although time sequencing could be one function carried out by the computer, the capabilities of the machine encourage use for more complex tasks. The timing capability could still be used, for instance, to alter temperature set points and minimum ventilation rates as the housed animals matured, or to match diurnally varying requirements, but the main task of the software is more likely to be the integrated control of the environment.

The control strategy can be of varying levels of complexity. If the object of control were simply to maintain a single variable, such as temperature, at a given level or within given limits, the software could implement one of the classical control algorithms, such as PID control, or a variation of these. A producer, however, is likely to impose further requirements. Thus, minimum ventilation rates need to be recognized as does the need to interlock the operation of related equipment such as ventilation fans, ventilation openings and heaters. The software could also be required to optimize energy use by minimizing heat loss and the use of supplementary heat within the building, and will almost certainly be required to trigger alarms in the event of failure of parts of the system.

As more suitable sensors are developed and more becomes known about other factors in the environment, there will be increased incentives to include these in control strategies. Thus, under cold climatic conditions and low ventilation rates, relative humidity rather than temperature can become the dominant concern. The software developer, in association with the user, must decide what relative humidities are tolerable, and what is the best or most economic strategy to combat excessive humidity while operating within temperature and energy-use constraints.

Further examples of increased control complexity will come from the use of gas or pollutant concentrations as secondary controllers of ventilation rate. Although air temperature is likely to remain the primary control parameter for ventilation rate, the use of CO₂ concentration as a basis for ventilation control has been proposed, at least in establishing minimum rates (Owen, 1982). Recent monitoring work has shown that, at least with some species, the concentration of CO₂ could be used, together with age or weight data, to provide a good indicator of ventilation requirements (Feddes, Leonard and McQuitty, 1984). Monitoring of commercial poultry laying units (McQuitty, Feddes and Leonard, 1984) has also shown that the concentrations of gases such as NH₃ can exceed proposed threshold limit values and should be used instead of moisture control in certain circumstances to establish minimum ventilation criteria. As more data become available on the effects of high concentrations of air contaminants, and assuming that management practices do not change, there will be a need to control ventilation rates to reduce these concentrations. This could be implemented easily by modified control software as long as suitable sensors are available.

In summary then, control software can be developed to virtually any level of complexity so long as suitable management information is available and there are suitable sensors to collect the data required. The ability of the computer to handle this information has at present far outstripped our ability to provide the information to the computer.

The third function of the software is to initiate the transmission of data to the real world. These data may be in the form of electrical signals to turn equipment on and off or it may be in the form of displays or printed records for the operator or management. The complexity of this part of the software depends on how many components are to be controlled and how much data are required by the operator, all of which need to be specified in detail before the software is written.

The problem of specifying the requirements of the software before it is written should be emphasized. The computer will do only what it is told by the software. Although software can be written to compensate for deficiencies in sensors and knowledge of the response characteristics of the system, the computer cannot correct bad management strategies, wrong assumptions and incorrect information. The writer of software, therefore, must know exactly what is to be controlled, and

what equipment is to be used and how it will be used. Since the development of software is an expensive exercise, there is a strong argument for standardization of barns, equipment and management practices so that software can be standardized and its cost spread over many installations.

The actual interfacing of the computer with the equipment to be controlled must also take into account the characteristics of the equipment. Switching of electrical devices often results in high voltage transients from which the computer must be isolated. Normally, the computer will be capable only of transmitting direct current control signals of low voltage and low amperage and, hence, switching devices must be compatible with the computer output. One suitable way of interfacing the computer with the controlled equipment is by means of optically isolated triacs. These devices provide electrical isolation of the computer from high voltage, alternating current loads, which are switched by means of an optical signal generated by the low-level electrical signal from the computer.

Practical applications

Although Bundy, Dvorak and Mangold (1982) have described a microcomputer-based system for environment control in a farrowing house and Boon (1984) has described an experimental system for finishing pigs, computer control of environment seems to have enjoyed more widespread application (or experimentation) in the poultry industry. At least one computer-based 'turn-key' system for environment control in poultry housing is available in Europe and systems are either available or under development in north America. Unfortunately, little or no data are available publicly on the performance of these systems, but several experimental systems have been reported in the literature. These reports all illustrate, to some extent, the different aspects of computer control of environment that have been discussed above.

Mitchell and Drury (1982) compared microcomputer-based and 'conventional' systems used to control a solar-heated, poultry brooding system. The microcomputer was able to implement a much more complex control strategy than the conventional system which used solid state or 'hard-wired' logic. The computer-controlled system gave slightly greater solar heat collection and a much lower requirement of supplemental heat when compared with the conventional system. Much of the difference in heat requirement was probably due to the fact that, in the conventional system, heating and ventilation control were independent whereas they were interlocked in the computer-based system. The complex control strategy, including the heating-ventilation interlock, was implemented purely in software.

Kay and Allison (1983) and Worley and Allison (1984) have described the development of a microprocessor-based system for control of heating and ventilation systems in broiler houses. This system was designed to operate ventilation fans, inlets and heaters and to vary the set-point temperature both diurnally and with the age of the housed birds. Relative humidity and NH_3 concentration were proposed as secondary control parameters but, due to the lack of a suitable NH_3 sensor, only relative humidity sensing was implemented. Although the system was not field tested, the software was written for a clearly specified barn and associated equipment. Apart from illustrating the need for such specification, this allowed a computer simulation of computer-based and conventional controls to be carried out. This simulation indicated that substantial

energy savings could be expected from the use of computer control instead of conventional systems.

A computer-based heating and ventilation controller for broiler houses has also been developed at the National Institute of Agricultural Engineering in England (Moulsley, 1984). This system was developed to cope with the complexity of proposed control tasks and considerable effort, in the form of prior monitoring and mathematical modelling, was devoted to obtaining full specifications of the controlled system. Although the cost of software development is not mentioned in the above reference, the point is made that the hardware required is cheaper than for conventional systems. Field tests of the system gave satisfactory temperature control although a reliability problem due to a lightning strike was encountered.

Just as the NIAE system was based on previous monitoring of the environment in broiler barns, so too was a preliminary study of computer control carried out by Leonard *et al.* (1984). The monitoring work was part of a continuing programme of studies on the environments in commercial animal production units and is reported elsewhere (Feddes, Leonard and McQuitty, 1984; Leonard, Feddes and McQuitty, 1984). During the course of this work, a decision was made to demonstrate the feasibility of computer control of one of two broiler barns that were monitored.

Subsequently, a barn was controlled for three consecutive 24 h periods by two computers running different programs and by the thermostat system installed in the barn. Under computer control, temperatures of the barn air were sensed by thermistors which were located, on the basis of data gathered during the monitoring phase, to provide reliable readings of mean barn conditions. The minimum ventilation rate and temperature set point were specified by the owner of the barn, who was an experienced and conscientious manager and who also set the thermostats to provide these conditions. The experiment was of very limited duration and scope, but served to highlight some of the points made above.

The outside temperatures were similar for all three control periods and the two computers gave marginally better temperature control than the thermostat system. However, the main feature of the results was the difference in supplemental heat usage under the computer and conventional control systems. Since there was no interlock between the fan and heater thermostats, the computer systems were expected to show a marked saving in heater energy. In fact, the reverse was the case. The thermostat system, set by the normal operator, underventilated the barn during the cool night hours and the heater was not called upon at all. With the computer-based systems, ventilation was maintained at or above the minimum level specified and, consequently, supplementary heat was used during the night in both computer-controlled periods. Either the operator did not specify his required minimum ventilation rate adequately or he did not understand the way in which his thermostats controlled the ventilation rate. If the latter were the case, then the computer software proved less fallible than the human operator, although there were some problems.

Despite the previous monitoring, the time response of the system was not adequately accounted for in the computer software. This resulted in some overshooting during heater operation. Also, the wiring for the control systems was installed some time ahead of the actual experimental runs and, although not designed to be a permanent installation, severe corrosion of exposed wiring and terminals was noted in the barn environment. This was exacerbated by the apparent appetite of mice for wiring insulation and caused a number of problems with poor connections.

Conclusions

1. The total environment inside an animal housing structure is very complex and cannot be described simply by temperature. Control of this environment may be achieved by using temperature as a primary indicator, but other variables need to be sensed and embodied in the control strategy.
2. The increased complexity implied by total environment control calls for computer-based controllers, but the major impediment to such control is the lack of suitable sensors and the lack of data pertaining to various components of the environment.
3. A major advantage of computer control is the facility to change the software, which can be as complex as desired, without altering the hardware of the system. However, the development of software is expensive.
4. Considerable design effort is required to ensure that a computer-based system will operate satisfactorily in a barn environment. This implies taking steps to overcome the effects of moisture, dust, rodent attack and electrical noise.
5. Computer control of the environment in animal housing is a technical reality. However, much work is required in order to utilize the full capacity of computers in this area.

References

- BAXTER, S.H. (1969). The environmental complex in livestock housing. *Farm Building Report*, No. 4. Scottish Farm Buildings Investigation Unit, Aberdeen. 62 pp.
- BOON, C.R. (1984). The control of climatic environment for finishing pigs using lower critical temperature. *Journal of Agricultural Engineering Research*, **29**, 295–303
- BRUCE, J.M. (1981). Ventilation and temperature control criteria for pigs. In *Environmental Aspects of Housing for Animal Production*. pp. 197–216. Ed. by Clark, J.A. Butterworths, London
- BRUGGER, M.F. (1982). Specifications for environmental control in dairy production: ventilation of stall barns. In *Proceedings, Symposium on Management of Food Producing Animals*. Vol. II. pp. 928–937. Purdue University, Lafayette, Indiana
- BUNDY, D.S., DVORAK, R.E. and MANGOLD, D.W. (1982). Utilizing a microcomputer for controlling the environmental systems in a swine farrowing building. In *Livestock Environment*, II. (Proceedings, Second International Livestock Environment Symposium; pp. 247–256. American Society of Agricultural Engineers, St Joseph, Michigan
- CHARLES, D.R. (1981). Practical ventilation and temperature control criteria for poultry. In *Environmental Aspects of Housing for Animal Production*. pp. 183–196. Ed. by Clark, J.A. Butterworths, London.
- CLARK, J.A. and CENA, K. (1981). Monitoring the house environment. In *Environmental Aspects of Housing for Animal Production*. pp. 309–330. Ed. by Clark, J.A. Butterworths, London.
- CLOSE, W.H. (1981). The climatic requirements of the pig. In *Environmental Aspects of Housing for Animal Production*. pp. 149–166. Ed. by Clark, J.A. Butterworths, London
- COLE, G.W. (1980). The application of control systems theory to the analysis of

- ventilated animal housing environments. *Transactions of the American Society of Agricultural Engineers*, **23**, 431–436
- FEDDES, J.J.R., LEONARD, J.J. and MCQUITTY, J.B. (1984). Carbon dioxide concentration as a measure of air exchange in animal housing. *Canadian Agricultural Engineering*, **26**, 53–56
- GLENNON, C.R., MCQUITTY, J.B. and CLARK, P.C. (1984). 'Heat and moisture loads and air quality in commercial poultry rearing facilities.' CSAE Paper No. 84-405. Canadian Society of Agricultural Engineers, Ottawa
- HONEY, L.F. and MCQUITTY, J.B. (1976). Dust in the animal environment. *Research Bulletin* No. 76-2. Department of Agricultural Engineering, University of Alberta, Edmonton. 66 pp.
- KAY, F.W. and ALLISON, J.M. (1983). 'Microprocessor control of broiler house ventilation.' ASAE Paper No. 83-3029. American Society of Agricultural Engineers, St Joseph, Michigan
- LEONARD, J.J., FEDDES, J.J.R. CLARK, P.C. and MCQUITTY, J.B. (1984). Mini- and micro-computer control of the environment in a broiler barn. In *Agricultural Electronics—1983 and Beyond*. pp. 360–369. American Society of Agricultural Engineers, St Joseph, Michigan
- LEONARD, J.J., FEDDES, J.J.R. and MCQUITTY, J.B. (1984). Air quality in commercial broiler housing. *Canadian Agricultural Engineering*, **26**, 65–71
- MCQUITTY, J.B., FEDDES, J.J.R. and LEONARD, J.J. (1984). 'A comparison of air quality in three commercial laying operations.' ASAE Paper No. PNR 84-302. American Society of Agricultural Engineers, St Joseph, Michigan
- MITCHELL, B.W. and DRURY, L.N. (1982). Microcomputer and conventional solid-state controls for a solar heating system. *Transactions of the American Society of Agricultural Engineers*, **25**, 1081–1090
- MOULSLEY, L. (1984). Cheaper broiler house control by computer. *Poultry World*, **24**, 16–17
- OWEN, J.E. (1982). A design basis for ventilation of pig buildings. In *Livestock Environments*, II. (Proceedings, Second International Livestock Environment Symposium). pp. 406–410. American Society of Agricultural Engineers, St Joseph, Michigan
- REECE, F.N. (1982). Specifications for environmental control in poultry—ventilation and temperature. In *Proceedings, Symposium on Management of Food Producing Animals*, Vol. II. pp. 260–270. Purdue University, Lafayette, Indiana
- WATHES, C.M., JONES, C.D.R. and WEBSTER, A.J.F. (1983). Ventilation, air hygiene and animal health. *Veterinary Record*, **112**, 554–559
- WEBSTER, A.J.F. (1981). Optimal housing criteria for ruminants. In *Environmental Aspects of Housing for Animal Production*. pp. 217–232. Ed. by Clark, J.A. Butterworths, London
- WORLEY, J.W. and ALLISON, J.M. (1984). 'Microprocessor control of poultry house environment.' ASAE Paper No. 84-3025. American Society of Agricultural Engineers, St Joseph, Michigan
- YOUNG, B.A. and DEEGAN, A.A. (1981). Thermal influences on ruminants. In *Environmental Aspects of Housing for Animal Production*, pp. 167–180. Ed. by Clark, J.A. Butterworths, London

COMPUTER CONTROL OF BROILER HOUSE VENTILATION AND HEATING

G.L. VAN WICKLEN and J.W. WORLEY
University of Georgia, Athens, USA

Introduction

The south-eastern USA is a region which is subject to warm humid summers with outdoor air temperatures as high as 40°C, and a short winter season with temperatures as low as -20°C. This region produces approximately 2 billion broiler chickens per year, nearly half the total broiler production of the USA. In a climate with these temperature extremes, the predominant type of broiler housing (conventional housing) consists of structures with curtain sidewalls utilizing natural ventilation with a minimum of insulation and environmental control. Enclosed, insulated, mechanically ventilated broiler housing, which is known as environmentally controlled housing, has been more willingly adopted in colder climates of the USA compared to the south-east. The reluctance of southern poultry growers to adopt environmentally controlled housing is not difficult to explain. A study of fifteen poultry companies (integrators) in Georgia revealed that energy consumption in environmentally controlled housing exceeded that of conventional housing for propane by 88%, and for electricity by 142% (Lance, 1979). The increased energy consumption is surprising, considering studies by Hughes and Weaver (1975) and by Baughman and Parkhurst (1977) which indicated advantages in energy savings and broiler performance using environmentally controlled housing. It is apparent that management of the environment and/or structural components differ between commercial poultry housing and research facilities. Proper building materials are a matter of selection and deficiencies can be corrected. Management practices, especially control of ventilation flow rates and supplemental heating, frequently deviate from those recommended and are likely to contribute to excessive energy consumption in environmentally controlled housing. Among the most expensive phases of broiler production is brooding during the first 4 weeks of the growth cycle. Large amounts of expensive liquefied propane (LP) gas are necessary for supplementary heating, especially during cold weather. The accumulated energy consumption per kg of bird for LP gas, electricity and feed was found to be highest during the first 4 weeks of the growing cycle of a flock raised during winter in environmentally controlled housing (Baughman and Parkhurst, 1977). A control unit is clearly necessary to manage the ventilation system properly.

An economical means of providing heat for brooding is also needed as well as the means to control its use. LP gas cost Georgia poultrymen US \$25.2 billion during 1980. Cord wood and wood chips are among the biomass materials abundantly available in the south-eastern USA. A system consisting of a furnace with a water jacket, circulation system, storage tank, and a heat exchanger to utilize wood as a source of brooding energy has been proposed (Thompson, Stuckey and McLendon, 1983) as an alternative to expensive LP gas heat.

A microprocessor-based control system was chosen to control the management of the ventilation and the wood heating system for an environmentally controlled broiler house. This control system should be capable of conserving energy through proper management, simple for the poultry grower to operate, and economically feasible for a broiler house in the south-eastern USA.

Ventilation control

The initial phase of this project has been dedicated to development of a microprocessor-based control system for an environmentally controlled broiler house. The primary objectives were to develop a control system to maintain the desired environment within the broiler house, to develop a computer simulation of the broiler house environment to determine potential energy savings, and to test the control system in laboratory and commercial locations.

PROCEDURE

A broiler house measuring 12.2m $\times$ 121.9m $\times$ 2.1m, utilizing partial (half) house brooding was simulated using an Apple II+ computer. The purpose of this simulation was to compare energy consumption and environmental control using conventional thermostat controls with that of a microprocessor-based control unit. The simulated ventilation system consisted of ten fans, each of capacity 4.72 m³ s⁻¹, which caused air to enter through a continuous inlet slot at the top of the sidewall. The opening width of the inlet slot was controlled by an adjustable baffle board. One of the ten fans was of variable speed. Outdoor conditions were simulated using weather data supplied by the US Weather Bureau for Athens, Georgia. The weather data used included (1) a 5-year average of data for both January and July, (2) the warmest and coldest days during a 5-year period, and (3) an extremely humid day when the outdoor air remained nearly saturated for the entire day.

A control program was written in Motorola BASIC-M which would establish the desired temperature within the broiler house and operate the heating system during brooding (*Figure 14.1*). A diurnal air temperature variation, as suggested by Siegal and Drury (1969) and Deaton *et al.* (1973), was included. The ratio of the outside absolute humidity to the inside absolute humidity (ROH) was also used as a control parameter to prevent overventilation when the outdoor humidity was above that desired indoors. The inside temperature was determined by the average of several sensors located over the length of the house at bird height. The ventilation rate was at full capacity when the actual inside temperature exceeded the desired inside temperature by 8.33°C and varied linearly from the desired temperature up to that point. Heaters were turned on when the inside temperature fell 1°C below the

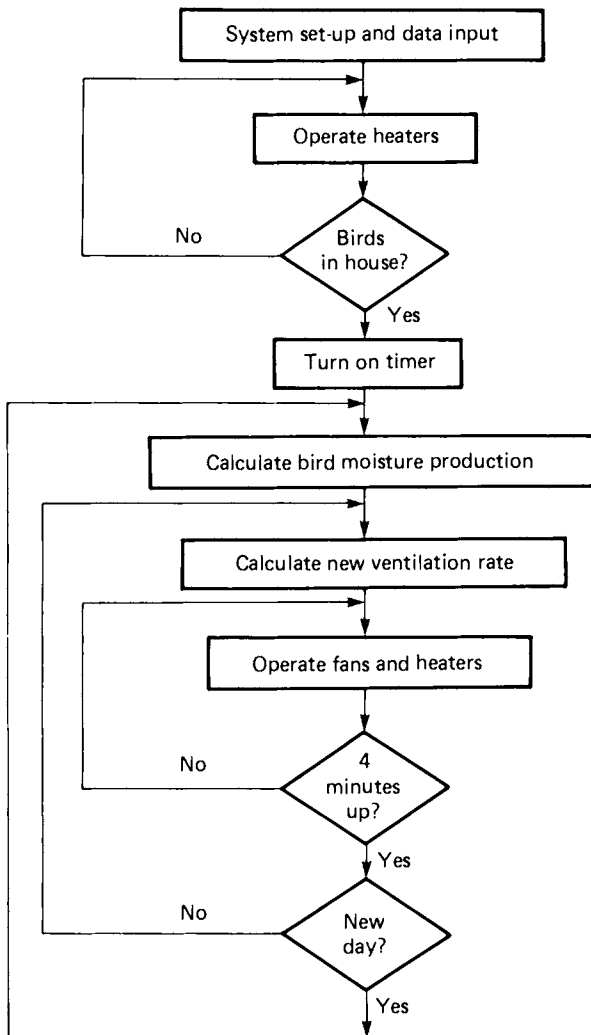


Figure 14.1 Flow diagram for the control program

desired temperature. If the inside relative humidity was exceeded, the ventilation rate was increased to replace humid air with relatively dry outdoor air.

A hardware system was developed to be used for field application of the control unit. Prior to placement in a field location, a system consisting of AD590 temperature sensors, a Honeywell Dew Probe, and a Motorola Exorset DS35 Development System with a MC6809 microprocessor was used to test the control of fans and heaters inside an environmental chamber designed to simulate a poultry house. The simulated poultry house measured $2.26\text{ m} \times 2.13\text{ m} \times 7.32\text{ m}$, and was constructed of 19mm extruded polystyrene insulation. Bird heat and moisture production were simulated using humidifiers and a 2200 W electric heater. Outside air conditions were simulated using air from an adjacent environmental chamber.

Following the initial testing of the hardware in a laboratory environment, a field test was done in a broiler house without birds. This test was done to ensure the operation and reliability of the control system. The hardware used for this test included a Honeywell Dew Probe, thermocouples connected to an Analog Devices Micro Mac interface system, and a Motorola M68MM17 single board computer to control the system. An independent system consisting of a Monitor Labs Data Logger with thermocouples and a Commodore 64 computer was used to monitor the environmental conditions arising from the control system. Electric heaters embedded in a concrete floor were used to provide a heat load, simulating warm weather conditions. Cold weather conditions were not simulated. The control unit was tested for 30 days during which a series of 24 h tests were done investigating the environmental control using different diurnal temperature variations, bird ages, and outside weather conditions.

RESULTS

The simulation program compared the energy consumption in broiler housing using conventional thermostat control to an environment controlled by a microprocessor

Table 14.1 COMPARISON OF ENERGY REQUIREMENTS, DURING THE BROODING PERIOD, OF MICROPROCESSOR *VERSUS* CONVENTIONAL CONTROL FOR FULL- AND HALF-HOUSE BROODING

		<i>Supplemental heat required (MJ)</i>	<i>Ventilation air required (1000 m³)</i>
<i>Full-house brooding</i>			
5-year	Microprocessor	19972	2304
January	Conventional	21333	3107
average	% Difference	6.4	25.8
Worst	Microprocessor	45165	1738
January	Conventional	48182	2819
day	% Difference	6.3	38.3
5-year	Microprocessor	611	31493
July	Conventional	952	41165
average	% Difference	35.8	23.5
Worst	Microprocessor	351	55973
July	Conventional	629	54789
day	% Difference	44.2	2.2
<i>Half-house brooding</i>			
5-year	Microprocessor	6845	1850
January	Conventional	7832	2560
average	% Difference	12.6	27.7
Worst	Microprocessor	15820	1344
January	Conventional	18093	2290
day	% Difference	12.6	41.3
5-year	Microprocessor	292	18389
July	Conventional	412	24063
average	% Difference	29.1	23.6
Worst	Microprocessor	153	29375
July	Conventional	283	30178
day	% Difference	45.9	2.7

unit using a diurnal air temperature variation of 5.6°C. The comparison was made for both full- and half-house brooding situations. The microprocessor-controlled system exhibited energy savings of between 3% and 46% for the initial 4 weeks of the growth cycle. The results are listed in *Table 14.1*. The only exception was for the warmest conditions, when the microprocessor-controlled system had a 2% higher energy cost for ventilation, which would be likely to reduce the heat stress on the birds compared to a conventional control system. These results are even more impressive when one considers that conventional control systems in field situations are often mismanaged by the grower. The results of the simulation for average January conditions compare well with the results of Hughes and Weaver (1975) for supplemental heat needed (1.066×10^6 kJ per 1000 birds versus 0.97×10^6 kJ per 1000 birds). An energy consumption survey for similar housing in Georgia (Lance, 1979) revealed a yearly average supplemental heat requirement that is much higher (4.0×10^6 kJ per 1000 birds), clearly indicating that energy savings from a microprocessor-controlled system may be significantly greater than indicated by the simulation. It was found that when the ROH exceeded 0.9, the required ventilation rate to control indoor humidity was excessively high. The ventilation rate was limited to an economically feasible level in this instance.

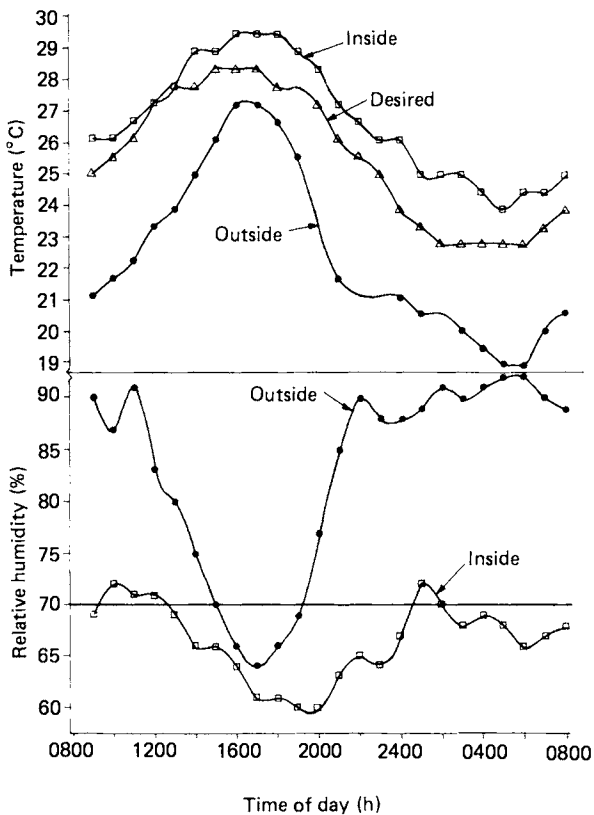


Figure 14.2 Environmental conditions in the full-scale poultry house. Bird age: 14 days. Diurnal temperature variation: 2.8°C

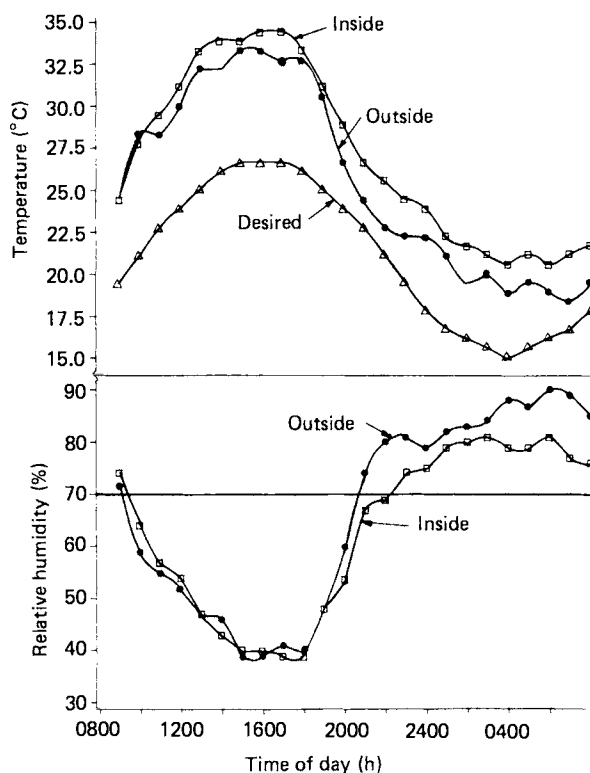


Figure 14.3 Environmental conditions in the full-scale poultry house. Bird age: 28 days. Diurnal temperature variation: 5.6°C

Despite problems with the environmental chamber which simulated a poultry house, the laboratory testing of the microprocessor-controlled system was successful. Heaters were turned on when the actual indoor temperature dropped 1°C below the desired level and remained on until the desired temperature was achieved. Ventilation for humidity control was initiated once the desired indoor temperature was attained.

The microprocessor-controlled system performed as expected in field testing in a house without birds but where bird heat and moisture production were simulated. The measurements indicated that the actual indoor temperature was usually held within an acceptable range of the desired indoor temperature (*Figures 14.2, 14.3 and 14.4*). Ventilation maintained the relative humidity below 70%, except when the ROH exceeded 0.9, as expected.

Brooding heat

The delivery of supplemental heat for brooding has been incorporated into the microprocessor control system. The control system performance has been analysed with respect to energy consumption using the assumption that LP gas furnaces heated air which was distributed through a perforated polyethylene tube to the birds. LP gas is the predominant fuel used for supplemental heat in broiler housing

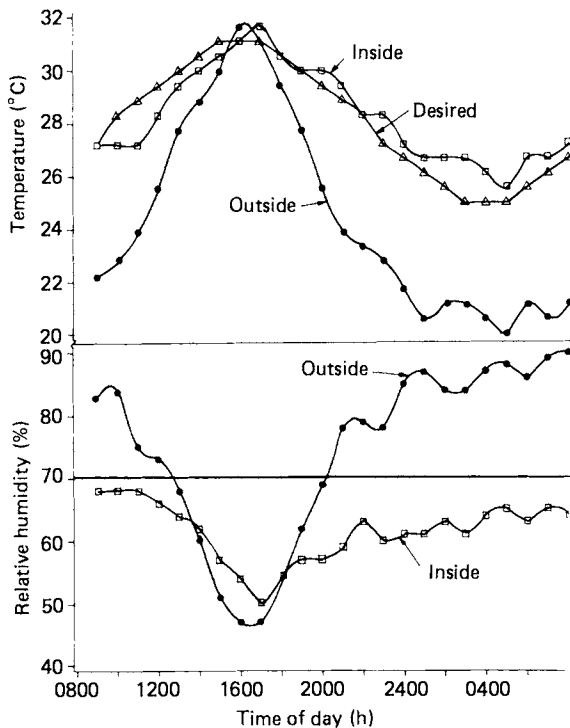


Figure 14.4 Environmental conditions in the full-scale poultry house. Bird age: 6 days.
Diurnal temperature variation: 2.8°C

(Lance, 1979), it is expensive, however, and alternate heat sources have been investigated.

Since cord wood and wood chips are plentiful in the south-eastern USA, the use of a wood-burning furnace which transports heat via water flowing in a pipe network has been examined. Thompson, Stuckey and McLendon, (1983) and Van Wicklen, Czarick and Duclos, (1984) have begun to adapt a computer control system to a heating system using a wood furnace to heat water. The water may be pumped directly to the poultry house, where it can be circulated through a rectangular network of PVC pipe which will exchange heat with the brooding environment, or the water may be pumped to or from an insulated concrete tank (Van Wicklen, 1984) buried below ground to be stored for later use. A microprocessor control system is almost mandatory for this heating system, because of the need for decisions involving properties of the biomass used, the furnace, changing weather conditions, heat required and produced by the birds, and the energy management of the heated water.

EXPERIMENTAL PROCEDURE

Control algorithms have been developed for the components of a biomass heating system for poultry. The thermal analysis of a typical wood-burning furnace and a water transport system was completed (Thompson, Stuckey and McLendon, 1983).

The heat transported to the young birds from the heated water circulating through a PVC pipe brooder resting on the floor litter was analysed (Van Wicklen, Czarick and Duclos, 1984).

In order to determine the thermal efficiency of the furnace, water oak at approximately 13% and 30% moisture content was burned in a batch-type burner manufactured by Dumont Industries. This draught-induced burner had a water jacket to heat the water. Temperatures reached nearly 1100°C in the combustion chamber, ensuring nearly complete combustion with almost no creosote formation. Heated water from the furnace was pumped to a 3600 ℓ concrete tank buried 0.3 m below ground. A heat exchanger was used to remove heat from the tank to simulate heat delivered to the brooding environment. Temperatures and water flow rates were monitored throughout the system, including points in the ground adjacent to the storage tank. Copper-constantan and chromel-alumel thermocouples were used for temperature measurements. Cox Instruments Series 21 flow transmitters were used to determine water flow rates. Temperature and flow rate data were monitored using the Monitor Labs 9302 Data Logger, which is built around a microcomputer. A control program was written which requires the entry of bird age, number of birds, brooding temperature, house dimensions and thermal resistance, forecasted 3-day daily high and low temperatures, and properties of inside and outside air. Using characteristic properties of the wood, the wood furnace, and the storage system, the amount of supplemental wood heat could be determined for the following 3-day period.

The thermal analysis of a PVC pipe brooder was completed. This brooder consisted of a continuous length of PVC pipe fixed in a rectangular configuration (*Figure 14.5*) which was placed on the floor litter. Young birds could receive heat by resting against the pipes or through radiation or convection heat transfer. A program was written to simulate the heat production by the pipe network which the birds could utilize. The simulation model was verified by comparing the simulated heat production to the heat production of a 17.5 m long prototype brooder in a ventilated growth chamber which was instrumented with thermocouples to monitor conductive and convective heat transfer through the chamber. Thermocouple and fan speed data were recorded by the Monitor Labs 9302 Data Logger, and were processed to determine heat exchange data and stored on a Commodore 64

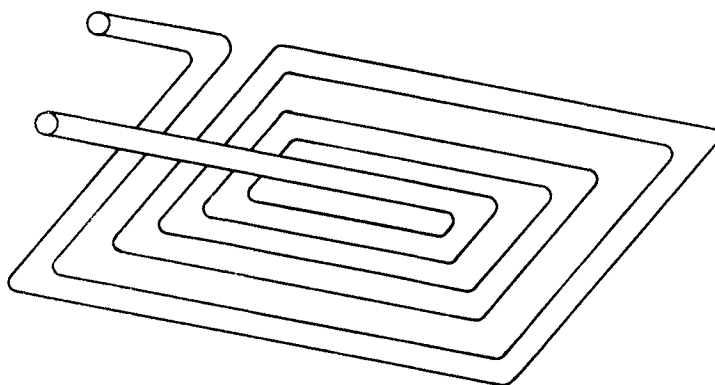


Figure 14.5 The PVC pipe brooder configuration

microcomputer. Various pipe diameters, lengths, spacings, inlet water temperatures and flow rates were investigated. Comparisons were made of pipes constructed from materials such as copper, steel and aluminium. The PVC pipe brooder prototype was tested with 70 commercial broiler chickens in the growth chamber to determine its usefulness.

RESULTS

The thermal analysis of the wood furnace and storage tank (Thompson, Stuckey and McLendon, 1983) resulted in an algorithm to predict the amount of wood necessary to provide heat for brooding. The algorithm was based on system heat losses totalling approximately 70% of the original heat value of dry wood (*Figure 14.6*). Some typical results using this algorithm are shown in *Table 14.2*.

The thermal analysis of a PVC pipe brooder resulted in the recommendation of an inlet water temperature of 50°C with a water flow rate of 0.032 $\ell \text{ s}^{-1}$ through nominal 32mm pipe. When the pipe brooder was constructed with a spacing of 0.15m between adjacent pipes, a brooding density of 0.005m² per bird was

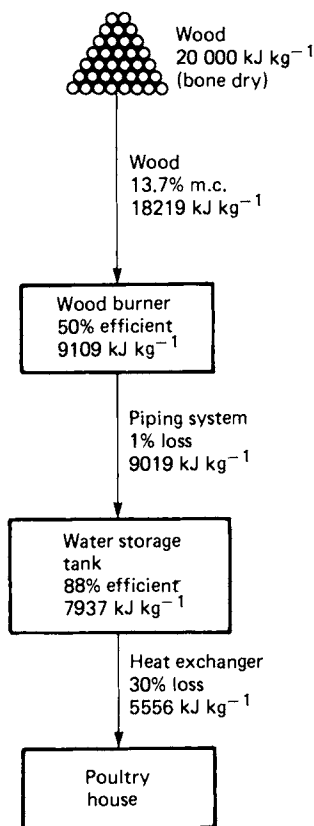


Figure 14.6 Thermal losses of a wood furnace heating system using a hot water storage system

Table 14.2 SAMPLE PREDICTIONS OF WOOD NEEDED FOR TYPICAL WEATHER AND POULTRY HOUSE CONDITIONS
(FIGURES PRESENTED AS CALCULATED)

<i>Bird age (days)</i>	<i>Temperature inside (°C)</i>	<i>RH inside (%)</i>	<i>Temperature outside (°C)</i>	<i>RH outside (%)</i>	<i>Bird heat (MJ h⁻¹)</i>	<i>Bird water (kg h⁻¹)</i>	<i>Vent rate heat (m³ min⁻¹)</i>	<i>Vent rate water (m³ min⁻¹)</i>	<i>Heat needed (MJ h⁻¹)</i>	<i>Wood needed (kg h⁻¹)</i>
1	32.2	70	-2	66	-3.7	10.6	0	8	183.7	30.6
1	32.2	70	20	71	-3.7	10.6	0	14	73.0	12.2
7	30.1	70	-2	66	35.6	44.7	0	39	201.2	33.5
7	30.1	70	20	71	35.6	44.7	0	77	64.9	10.8
14	27.1	70	-2	66	94.4	71.2	0	75	194.3	32.4
14	27.1	70	20	71	94.4	71.2	124	190	32.1	5.4
21	24.1	70	-2	66	198.4	104.4	41	135	171.3	28.6
21	24.1	70	20	71	198.4	104.4	625	532	0	0
28	21.1	70	-2	66	380.8	170.8	166	274	175.8	29.3
28	21.1	70	20	71	380.8	170.8	4780	4113	0	0

achieved and the brooding heat generated was similar to that of a suspended-type brooder burning LP gas.

The simulation program to predict heat from the brooder is presently being coordinated with the predictive algorithm to determine the quantity of wood needed to provide brooding heat. Work is in progress to implement computer control of feeding wood to the burner as needed and controlling the water flow rates both to the storage tank from the wood furnace and from the storage tank to the PVC brooders.

References

- BAUGHMAN, G.R. and PARKHURST, C.R. (1977). Energy consumption in broiler production. *Transactions of the American Society of Agricultural Engineers*, **20**(2), 341–344
- DEATON, J.W., REECE, F.N., KUBENA, L.L., MAY, J.D. and VARDAMAN, T.H. (1973). The effect of low vs. moderate rearing temperature on broiler performance. *Poultry Science*, **52**, 1175–1178
- HUGHES, H.A. and WEAVER, W.D. (1975). 'Energy savings in an insulated-fan ventilated broiler house.' ASAE Paper No. 75–4533. *American Society of Agricultural Engineers*, St Joseph, Michigan
- LANCE, G.C. (1979). Economic evaluation of controlled environmental and conventional contract broiler housing systems in Georgia. *Poultry Science*, **58**, 1423–1431
- SIEGAL, H.S. and DRURY, L.N. (1969). Broiler growth in diurnally cycling environments. *Poultry Science*, **49**, 238–244
- THOMPSON, S.A., STUCKEY, T.A. and MCLENDON, B.D. (1983). 'Predictive algorithm for heating broiler houses with cord wood.' ASAE Paper No. 83–3074. *American Society of Agricultural Engineers*, St Joseph, Michigan
- VAN WICKLEN, G.L. (1984). 'Insulation requirements for a buried heat storage tank.' ASAE Paper No. 84–4025. *American Society of Agricultural Engineers*, St Joseph, Michigan
- VAN WICKLEN, G.L., CZARICK, M. and DUCLOS, M.B. (1984). 'Design of a PVC pipe system for brooding chickens.' ASAE Paper No. 84–4027. *American Society of Agricultural Engineers*, St Joseph, Michigan

USE OF LOW-COST MICROCOMPUTERS FOR CONTROL OF ENVIRONMENT IN POULTRY HOUSES

F.N. REECE, B.D. LOTT and B.J. BATES

ARS South Central Poultry Research Laboratory, Mississippi, USA

Abstract

A low-cost computer was adapted to measure temperature, control brooder stoves and ventilation fans, and raise or lower sidewall curtains. A computer program was developed to describe mathematically and to control the parameters required to maintain the required temperature and relative humidity (RH) to brood and grow broiler chickens. The system has operated a poultry house to grow broilers during winter at the USDA South Central Poultry Research Laboratory in Mississippi and has been used on commercial broiler farms in the states of Mississippi, Alabama, and Arkansas.

Introduction

The temperature required for growing broiler chickens commercially starts at about 29°C post-hatch and decreases linearly during the brooding period to 21°C at about 21 days of age. After 3 weeks of age, broilers can be grown over a rather wide range of environmental temperatures. Temperatures between 21°C and 10°C do not depress growth rate but will increase the feed:gain ratio. Between 21 and 35°C, feed:gain ratios are unaffected but growth rate is depressed (Deaton *et al.*, 1972; Deaton, Reece and McNaughton, 1978; Reece and Lott, 1983).

During brooding and when growing temperatures are kept within the 15–27°C range, RH should be maintained at $60 \pm 10\%$, primarily to control the moisture content of the litter so as to avoid excessive dust from dry litter or ammonia from wet litter (Reece and Lott, 1982a,b). RH should be kept below 50% during hot temperatures (above 27°C) to avoid excessive growth depression and possible heat prostration (Winn and Godfrey, 1967; Reece, Deaton and Kubena, 1972).

Reece and Lott (1982a) described equations used for calculation of ventilation rate to control RH, based on chicken latent heat production and climatic conditions. Latent heat (moisture) production of broiler chickens has been determined for the brooding period and for the growing period by Reece and Lott (1982b,c).

The objective of the work reported here was to develop a low-cost computerized environmental control system and associated computer programs to operate

brooder stoves and ventilation fans, and to open and close sidewall curtains to maintain temperature and RH in broiler houses for optimum broiler performance.

Materials and methods

HARDWARE

Initially, a Commodore VIC-20* computer with about 3500 bytes of useful memory was used (Reece, Lott and Bates, 1985). Although this small computer was adequate when only brooder stoves and ventilation fans were controlled, it did not have sufficient program storage capacity to control the operation of the sidewall curtains in addition. Therefore, additional experiments were conducted using a Commodore 64* computer which has about 36 kbytes of useful memory. This low-cost unit, based on an 8-bit 6510 microprocessor, is used primarily for video games and personal use. It has an expansion port (for game cartridges), video port (to connect a video monitor), serial port (to connect a printer), cassette port (for tape cassette), and a user port (for special accessories).

Electrical connections were made to the expansion port for measuring temperature, controlling equipment, and program input. Temperature was measured by applying a regulated voltage to a thermistor-resistor circuit. The analogue output from this circuit was proportional to the temperature of the thermistor and was converted to digital form by an Analog Devices AD7581*, 8-bit, eight-channel data acquisition system. Two thermistor-resistor circuits were used, one for temperature measurement outside the house and one for temperature measurement inside the house. Each circuit was connected to a separate channel on the AD7581 which, in addition to analogue-to-digital conversion, also performed the multiplexing (switching) for selecting inside or outside temperature to be measured. The AD7581 and four Crydom D1202* solid state relays for controlling fans, stoves and the curtain operation were connected to the computer expansion port through an interface adaptor integrated circuit. The Commodore 64 requires a 6526 interface adaptor chip. The programs were stored on a Cartridge-64†, which contained two erasable, programmable, read-only 2764 memory chips (EPROMS). Program storage was done with a Cartridge-Maker-64†. The edge-board connector of the EPROM cartridge served the dual purpose of inputting the program to the computer, and connecting the measuring-control circuit through the computer expansion port. *Figure 15.1* shows the schematic diagram for the temperature-measuring circuit and power supply; *Figure 15.2* shows the interface between the measuring and control circuits and the computer; and *Figure 15.3* shows how the interface was connected to the controlled devices. The major components required for the system are listed in *Table 15.1*. A small TV set, connected to the video port, was used to monitor operation of the system.

*Trade names in this article are used solely to provide specific information. Use of trade names does not constitute a guarantee or warranty by US Department of Agriculture (USDA) and does not signify that the product is approved to the exclusion of other comparable products.

†Available from Custom Programming Group, Exton, Pennsylvania, USA.

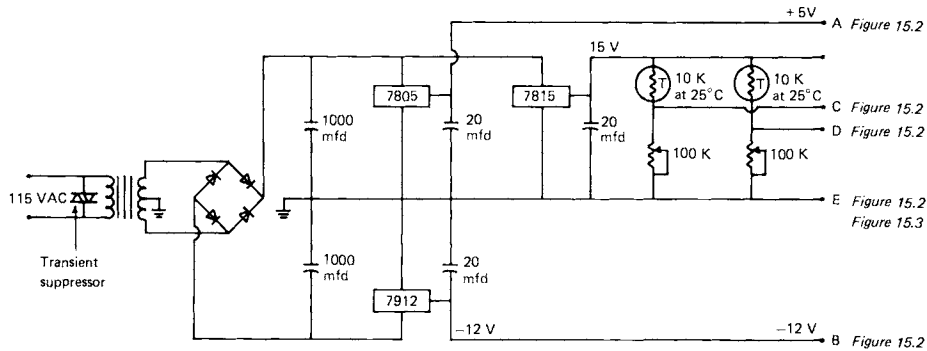


Figure 15.1 Schematic diagram for the temperature-measuring system for a low-cost computer

Table 15.1 COMPONENT DESCRIPTION* FOR ASSEMBLY OF SYSTEM SHOWN IN FIGURES 15.1, 15.2 AND 15.3 FOR USE WITH COMMODORE 64 COMPUTER TO CONTROL POULTRY HOUSE ENVIRONMENT

Component	Description	Number required
<i>Figure 15.1</i>		
Thermistor	Keystone No. 2012-5506-120 10 K ohms at 25°C, $\pm 10\%$ $\frac{\text{Resistance at } 0^\circ\text{C}}{\text{Resistance at } 50^\circ\text{C}} = 11.41$ Dissipation = 7.2 mW/°C	2
Capacitors	1000 mfd, 50 V DC, electrolytic 20 mfd, 50 V DC, electrolytic	2 3
Transformer	Stancor PPC 13 115 V primary 30 V, 0.15 A, secondary, centre-tapped	1
Transient suppressor	General Electric V130LA20B Varistor	1
Rectifier bridge	International Rectifier 18DB4A 1.8 A, 400 V, full wave	1
Voltage regulators	Radio Shack 7805, +5 V output	1
	Radio Shack 7815, +15 V output	1
	Radio Shack 7912, -12 V output	1
Potentiometer	Bourns 3006 P-1-104 100 K ohms, $\pm 10\%$, adjustable 1.25 W	2
<i>Figure 15.2</i>		
Integrated circuit	6526 I/O chip	1
Analogue/digital converter, multiplexer	Analog Devices AD 7581 data acquisition system, 8-bit, 8-channel	1
EPROM cartridge	Custom Programming Group Cartridge-64, 16 K, erasable, programmable, read-only memory	1
<i>Figure 15.3</i>		
Solid state relay	International Rectifier Crydom D1202 relay, 3-32 V DC, input 120 V AC, 2.5 A output	4

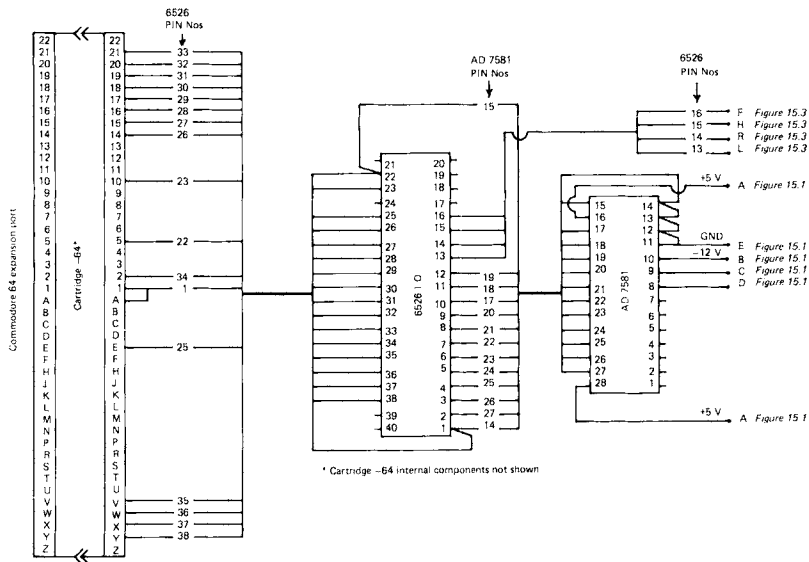


Figure 15.2 Connection diagram for the interface between the computer and the temperature-measuring system (*Figure 15.1*) and equipment controllers (*Figure 15.3*)

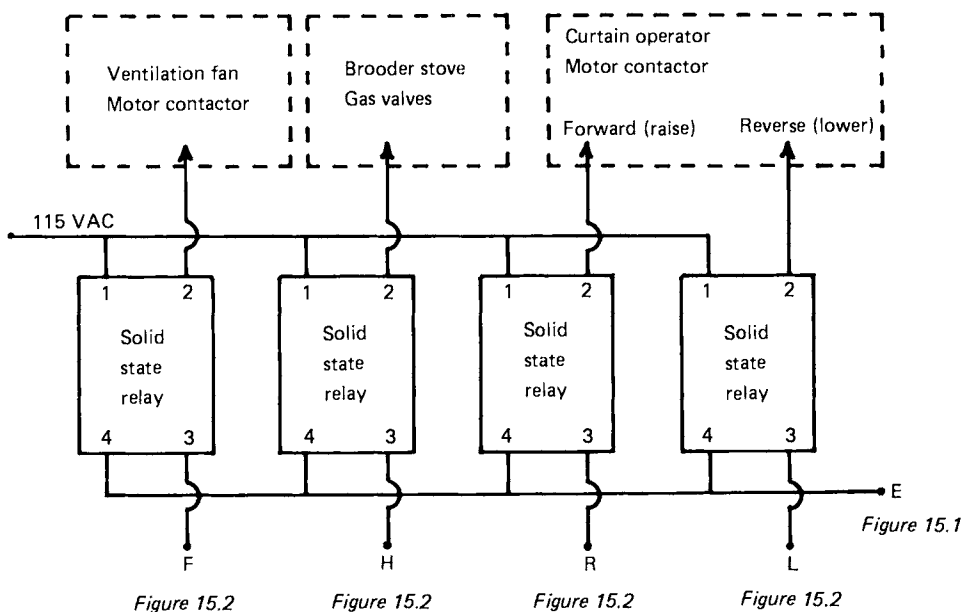


Figure 15.3 Schematic diagram for connecting the computer interface (Figure 15.2) to the poultry house equipment to be controlled by the computer

SOFTWARE

The programs, written in Microsoft* BASIC, used a time-proportioning control technique for temperature control based on the general equation

$$t_0 = \frac{(T - T_s)}{B} \tau$$

where T_s = set temperature to be maintained ($^{\circ}\text{C}$), T = actual temperature measured ($^{\circ}\text{C}$), B = proportional band ($\pm ^{\circ}\text{C}$) above and below T_s , τ = cycle time (s) and t_0 = fan or brooder stove on-time (s cycle^{-1}).

When $T < T_s$, brooder stoves were turned on. When $T_s < T < (T_s + D)$, $t_0 = 0$, neither brooders nor fans were turned on for temperature control, where D = dead band ($^{\circ}\text{C}$). When $T > T_s + D$, the fan 'on-time' was determined by

$$t_0 = \left[\frac{T - (T_s + D)}{B} \right] \tau$$

When $T > T_s + D + K$, the fans were inactivated and sidewall curtains were opened an incremental amount to provide cooling through natural ventilation (K = an arbitrary constant, $^{\circ}\text{C}$). Curtains were raised or lowered in incremental stages depending on whether temperature was rising or falling in the poultry house. The system reverted to fan and brooder stove operation when the curtains were fully closed and T dropped to equal T_s .

The proportional band (B), dead band (D), constant K and cycle time (τ) were selected arbitrarily; B , D and K were 1.7°C and τ was 300s. The temperature to be maintained (T_s) was calculated daily and was based on a starting temperature of 29.4°C , decreasing linearly to 21.1°C 21 days later, and maintained at 21.1°C to market age.

The ventilation rate for humidity control (V) was calculated by the procedure described by Reece and Lott (1984). This procedure requires only temperature measurement inside and outside the broiler house. The outside specific humidity was estimated by assuming that the outside dew point temperature approximated the outside temperature at 0600h each day. The inside specific humidity was estimated by linearization of the inside dry-bulb temperature–RH relation for RH between 50% and 70%. The program permitted adjustment of the inside RH, at the discretion of the system operator, between 50% and 70%. The calculated V was converted to the time-proportioning technique by the equation

$$t_0 = \frac{V}{V_c} \tau$$

where V = ventilation rate for humidity control; V_c = capacity of ventilation fans; τ = cycle time (s) and t_0 = fan on-time for humidity control (s cycle^{-1}).

Examination of the sensible and latent heat data reported by Reece and Lott (1982b) indicates that broiler chickens produce moisture and sensible heat, so that the RH of ventilation air changes little as it passes through a well-insulated poultry house. The result is that when outside RH is high, as normally occurs at night and on cool damp days, RH in the broiler house will be correspondingly high. Addition of sensible heat from another source, as from brooder stoves, can be used to lower the inside RH. Conversely, when outside RH is low, as normally occurs during midday on warm sunny days, inside RH will be correspondingly low, and moisture

can easily be removed from the house with a minimum addition of heat from brooder stoves. To take advantage of this phenomenon, a multiplication factor (MF), a function of outside RH, was used to increase ventilation rate when outside RH was low and decrease it when outside RH was high. The ventilation rate, calculated as described, was multiplied by the MF, which varied between 0.3 when outside RH was 100%, through 1.0 when RH was 60%, to 1.5 when outside RH was 25%.

The program was designed to make the calculations described every 5 min and to operate fans and brooder stoves, or sidewall curtains, during the ensuing 5 min, as indicated. Once each day, at 0600h, the values of the inside temperature to be maintained, broiler chickens size, and outside specific humidity (based on observed minimum temperatures) were calculated; these values were used for the ensuing 24h period. If an outside temperature observed during the ensuing 24h period was lower than that measured at 0600h, a new outside specific humidity was calculated and used until a new value was determined, either when a new lower temperature was observed, or at 0600h the next day.

Results and discussion

The system using the VIC-20 computer was connected to the ventilation fans and brooder stoves of an 11 m × 24.4 m environmentally controlled broiler house at the USDA South Central Poultry Laboratory in Mississippi. The system was used to control temperature and humidity in the house during the winter of 1983–84 for the 0–42 day brooding and growing period for 3600 broiler chickens. Full details of the results have been reported by Reece, Lott and Bates, 1985.

Table 15.2 shows a summary of the temperature control obtained by weekly periods, along with the climatic temperatures during the test period.

The average outside RH for the full period was 67.8%; the average inside RH was 58.2%. The RH inside the house tended to follow the outside RH, especially during the period of high outside RH during the second and third weeks and the period of low outside RH during the fourth week. Litter condition was acceptable throughout the experiment, although moderate caking occurred around feeders and waterers during the 6–10 day period, when both outside and inside RH were high. Ammonia levels were below 25 ppm throughout the experiment.

Table 15.2 MEAN OUTSIDE AND INSIDE TEMPERATURES COMPARED WITH THE PROGRAMMED, OR DESIRED, INSIDE TEMPERATURES. DATA FOR WEEKS 1 TO 6 OF A BROILER FLOCK TO TEST THE POULTRY HOUSE COMPUTER CONTROL SYSTEM

Week	Mean* temperature (°C)			
	Outside	Programmed inside	Actual inside†	Actual minus programmed
1	-0.2	28.2	27.5	-0.7
2	5.5	25.3	25.1	-0.2
3	4.7	22.3	22.4	+0.1
4	14.8	21.1	22.3	+1.2
5	12.6	21.1	21.4	+0.3
6	6.8	21.1	21.1	0.0

*Means of readings taken at 5-min intervals

†Temperatures measured near centre of brooding or growing area, 60 cm above floor

Total fuel for this experiment was 148 ℓ of liquefied petroleum gas per 1000 chickens. Fuel use *versus* time was very nearly linear, with about one-half of the fuel used during the first 23 days and the other half used during the next 23 days. The uniform fuel usage on a day-to-day basis indicated that the MF parameter was effective in preventing excessive fuel use on cool, damp days.

Systems using the Commodore 64 computer are currently in use on commercial broiler farms in the states of Alabama and Arkansas. A system using the Commodore VIC-20 computer has been used on a commercial farm in the state of Mississippi.

References

- DEATON, J.W., REECE, F.N., LOTT, B.D., KUBENA, L.F. and MAY, J.D. (1972). The efficiency of cooling broilers in summer as measured by growth and feed utilization. *Poultry Science*, **51**, 69–71
- DEATON, J.W., REECE, F.N. and MCNAUGHTON, J.L. (1978). The effect of temperature during the growing period on broiler performance. *Poultry Science*, **57**, 1070–1074
- REECE, F.N., DEATON, J.W. and KUBENA, L.F. (1972). Effect of high temperature and humidity on heat prostration of broiler chickens. *Poultry Science*, **51**, 2021–2025
- REECE, F.N. and LOTT, B.D. (1982a). Optimizing poultry house design for broiler chickens. *Poultry Science*, **61**, 25–32
- REECE, F.N. and LOTT, B.D. (1982b). Heat and moisture production of broiler chickens during brooding. *Poultry Science*, **61**, 661–666
- REECE, F.N. and LOTT, B.D. (1982c). The effect of environmental temperatures on sensible and latent heat production of broiler chickens. *Poultry Science*, **61**, 1590–1593
- REECE, F.N. and LOTT, B.D. (1983). The effects of temperature and age on body weight and feed efficiency of broiler chickens. *Poultry Science*, **62**, 1906–1908
- REECE, F.N. and LOTT, B.D. (1984). A procedure for determining poultry house ventilation. *Poultry Science*, **63**, 1076–1078
- REECE, F.N., LOTT, B.D. and BATES, B.J. (1985). The performance of a computerized system for control of broiler-house environment. *Poultry Science*, **64**
- WINN, P.N., JR, and GODFREY, E.F. (1967). The effect of temperature and moisture on broiler performance. *University of Maryland Bulletin*, No. A-153

MONITORING POULTRY HOUSE ENVIRONMENT

N.A. SUTCLIFFE, A.W.M. KING and D.R. CHARLES

Agricultural Development and Advisory Service, Nottingham, UK

Introduction

Our approach to the development and analysis of poultry house environments has four elements. The first is the assessment of the biological requirements of the birds by reviewing the results of response experiments.

Secondly, it is necessary to evaluate the financial consequences of deviations from the biological optima as determined in such experiments, so that the appropriate level of expenditure on controlling the environment can be judged. Recommendations and responses have been reviewed elsewhere (e.g. Charles, 1980, 1981b). Computer models based on the quantitative literature reviews can now be used for these first two stages (e.g. Charles, 1984).

Thirdly, practical housing and ventilation systems have been developed by the commercial ancillary trades, by ADAS, and by the National Institute of Agricultural Engineering, using a combination of the application of engineering principles and field experiences. Examples have been reviewed elsewhere by Carpenter (1981) and Charles (1980). Several standard designs are available.

These three stages have already received a good deal of attention; therefore over the last few years we have concentrated on the fourth stage. This consists in monitoring the physical performance of practical installations in order to test both that the intentions and recommendations are being achieved, and that the engineering of the designs used by the industry is sound. One of the most influential, and also one of the most easily measured, environmental variables is dry-bulb temperature, and this chapter describes attempts to monitor it.

Heat is gained by the building from birds, from heaters in the special case of brooding, and from solar radiation. Heat is lost via the ventilation air and through the structure. Simple house heat balance equations (e.g. Saville, Clark and Charles, unpublished) are available which enable the temperature lift above outside to be calculated. Conventionally, these equations ignore heat storage, solar heat gain, and floor heat losses, because these factors are not well understood and because they are believed to be relatively unimportant.

$$\Delta T = H/(1200V + UA)$$

where ΔT = temperature lift above outside ($^{\circ}\text{C}$), H = sensible heat production (W per bird), U = average thermal conductance of walls and roof, ($\text{W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$), A =

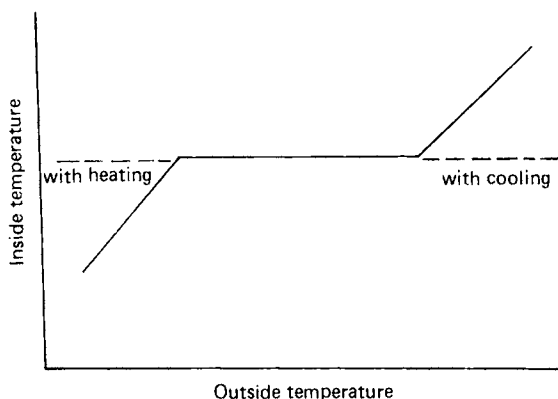


Figure 16.1 Zone of controllability: ideal variation of inside temperature with outside temperature

exposed area of walls and roof per bird (m^2); $1200 =$ volumetric heat capacity of air ($\text{J m}^{-3} \text{ } ^\circ\text{C}^{-1}$); and $V =$ ventilation rate ($\text{m}^3 \text{ s}^{-1}$ per bird).

Using such equations, it was pointed out by Spencer (1973) that for a fully stocked layer or broiler house there is theoretically a wide range of outside temperatures over which inside temperatures should be perfectly controllable by adjusting ventilation rates thermostatically. Thus, when inside temperature is plotted against outside, ideally the slope is close to zero over the controllable range (*Figure 16.1*); in reality, it is slightly greater than 0 because control sensors have to respond to a small temperature change. If heat storage is ignored, then when outside temperature exceeds the desired, or set, temperature, inside temperature can no longer be controlled and will rise with a gradient of 1 unless cooling is used. Similarly, as outside temperature falls, inside temperature will no longer be controllable once the ventilation rate has been reduced to its minimum. This minimum is determined by the needs of the birds for health and gas exchange, and has been reviewed for layers by Charles (1981a) and for broilers by Charles, Scragg and Binstead (1981). Spencer (unpublished) suggested that the slope of the linear regression of inside temperature on outside indicates the controllability of a ventilation system, where perfect control gives a slope of close to 0 and complete lack of control gives a slope of 1. He also suggested that the standard deviation of inside temperature provides an indication of the standard of windproofing and of stability of the system over time. No doubt these are slight oversimplifications, but we believe them to be useful guides and have therefore adopted a method of analysis based on his method.

Thus, our routine handling of the data involves, first, a simple trace of temperature against time for each channel and, secondly, a linear regression of inside temperature on outside temperature. The former provides a useful visual impression of the thermal performance of the house and, in particular, permits identification of any obvious errors or aberrations. It also provides collaborating producers with a clear and comprehensible guide to the spatial and temporal variations in temperature in their houses. The regression analysis provides a more objective assessment and permits some basis of comparison between systems. Before the regression is calculated, however, the potential width of the horizontal sector, which we have called the zone of controllability, is estimated by applying

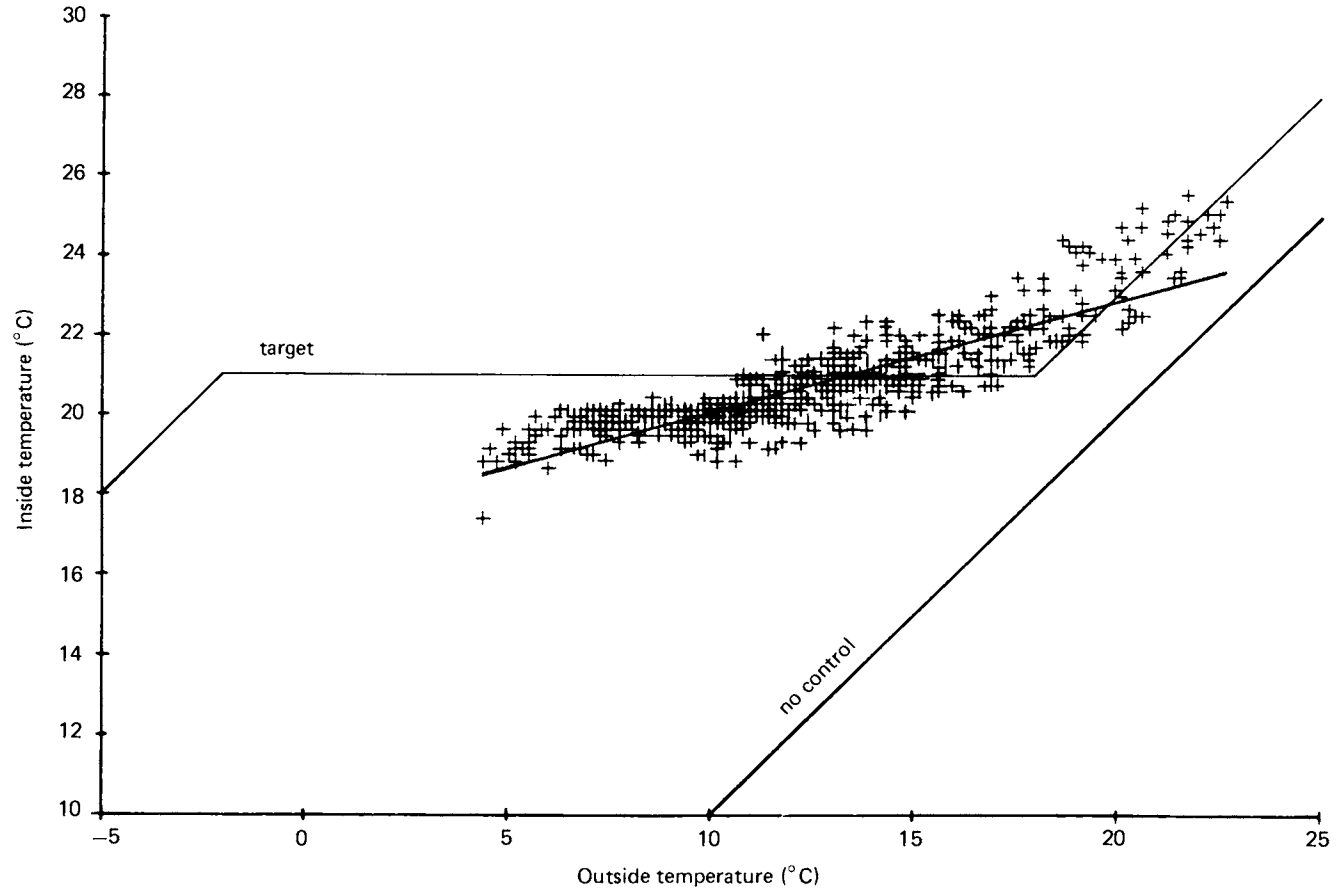


Figure 16.2 Plot of inside against outside temperature measured in the field. A line has been fitted to the plotted points (+)

the house heat balance equation to the specification of the house. The regression analysis is then confined to outside temperatures within this zone so that the slope can be legitimately compared with zero. *Figure 16.2* shows poor control.

Nearly all the available responses to temperature used in the egg production model, and taken from a review by Marsden (1981), referred to constant temperatures. The effects of temperature on biological and thus economic performance are quite pronounced, and have been reported elsewhere (e.g. Sutcliffe, unpublished). When layers are subjected to diurnal temperature cycles of moderate amplitude in which the panting threshold is not exceeded, they probably respond as if to the mean of the cycle according to experiments reviewed by Marsden (1981). In his own experiments an environment of 12 h at 24°C and 12 h at 18°C gave slightly superior performance to a constant 21°C, provided that the warm period coincided with the light part of the day. Egg production was non-significantly increased and food intake was non-significantly decreased.

Most of the published experiments on fluctuating temperatures for broilers refer to cycles used as palliatives during periods of very high peak daily temperatures. For example, Griffin and Vardaman (1970) found that cycles of 16–36°C were associated with better performance than were those of 24–36°C; Reece, Deaton and Kubena (1971) found that 24–35°C or 21–32°C cycles were more effective than constant 21°C at alleviating the effects of a subsequent exposure to 41°C for 2 h. Deaton *et al.* (1972) found that broilers exposed to a cycle of 24–35°C responded similarly to birds held at about the mean of the cycle (i.e. 29°C).

Using cycles whose mean was not so high, Griffin and Vardaman (1970) showed that fluctuations of approximately 17°C amplitude around a mean of 18°C gave responses similar to the mean. Compared with a constant 16°C, however, a cycling temperature of changing amplitude was associated with depressed growth rate. Siegel and Drury (1970) used symmetrical cycles around 21°C with amplitudes ranging from 6 to 17 Celsius degrees in three experiments and found a quadratic depression of growth rate as the amplitude increased above 6 degrees. Siegel and Drury pooled their three experiments in order to test for the curvature of response. Harris, Dodgen and Nelson (1974) found that a cycle of 18–29°C gave an inferior performance to that at a constant temperature of 24°C. Growth rate and food intake were depressed by 48 and 50 g per bird, respectively, from 21 to 56 days of age. Both these sets of investigations used unreplicated climatic chambers, though controlled to engineering standards. Unpublished experiments at Gleadthorpe Experimental Husbandry Farm, using large populations of birds in replicated rooms, have also shown a depression of growth rate due to fluctuating temperature (Binstead and Bray, unpublished data).

Perhaps, on balance, fluctuations in temperature are deleterious to performance of broilers, but symmetrical fluctuations of moderate amplitude below the panting threshold and synchronized with the photoperiod may not be harmful to layers, and might even be marginally beneficial. Whatever the consequences of moderate symmetrical fluctuations, there are two reasons why it is useful to examine the fluctuations of temperature over time in commercial houses. First, in a poorly controlled house the mean of a maximum and minimum thermometer reading may be misleading, since the diurnal temperature fluctuations are seldom symmetrical, and the time spent by the birds above and below the mean may be different. *Figure 16.3* shows a hypothetical case illustrating this. Presumably heat loss and therefore metabolic rate are likely to be functions of accumulated temperature (the integral of temperature with respect to time) in non-symmetrical cycles. Macleod (private

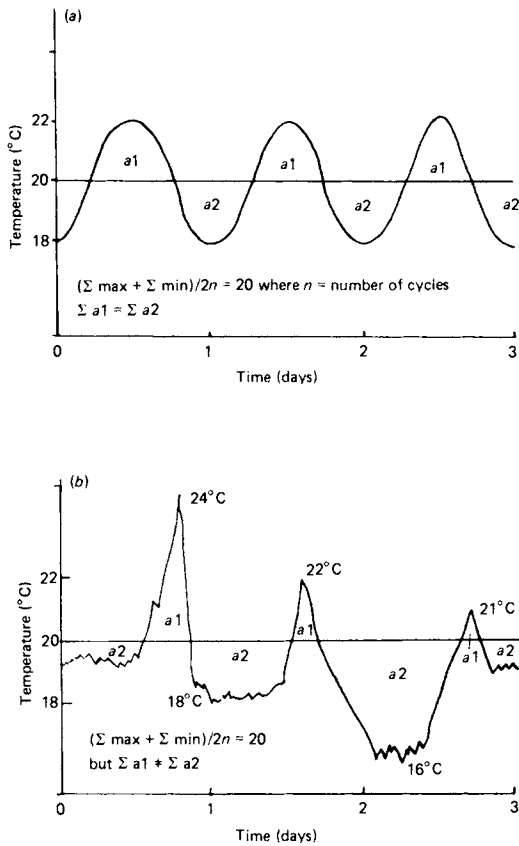


Figure 16.3 Symmetrical (a) and asymmetrical (b) temperature fluctuations

communication) considers that hour degree analysis is likely to provide an improved measure of the environment in fluctuating temperatures. Secondly, it is easier to hold the mean temperature at the precisely required level in a system which is inherently controllable and stable (Spencer, unpublished).

Materials and methods

EQUIPMENT

Data loggers

Two types of portable loggers were acquired: a Microdata 1600L (Microdata Ltd, Radlett, Herts, UK) and an Orion 3530 (Solartron Ltd, Farnborough, Hants, UK), each equipped to receive signals from temperature sensors and other transducers. In the early days the cartridges and cassettes were read in an ICL mainframe computer but latterly the loggers have been interfaced to an RML 380Z microcomputer (Research Machines Ltd, Oxford, UK), data being stored on disk

212 *Monitoring poultry house environment*

file and analysed using standard statistical packages developed by B Chadburn (ADAS CDU, Coley Park, Reading, UK).

Plotter

A Watanabe six-pen colour plotter (Environmental Equipment Ltd, Nantwich, Cheshire, UK), interfaced with the RML 380Z gives automatic handling of large amounts of data, displaying these in readily intelligible form and highlighting significant features of a given investigation.

Sensors

Though more costly than thermocouples or platinum resistance thermometers, thermistors were chosen because lightweight, screened, multicore cable and distribution boxes could be used to locate and distribute a large number of sensors over a wide area comparatively easily.

PROCEDURE

Ventilation systems tested

The existence of a wide variety of ventilation systems in the poultry industry, from the simple, manually operated convection-driven to the highly sophisticated computer-controlled fan-powered system, means that only a small sample can be monitored meaningfully. A decision was made to monitor initially the high-speed jet system in both cage and litter houses and natural ventilation in litter systems, in the hope of developing some ground rules concerning the behaviour of these systems in commercial installations. Additionally, the problem encountered commercially of poor productivity, with occasional deaths, during periods of extreme hot weather, has also been monitored.

Number and position of sensors

Poultry houses can be very large, in respect of both area and volume. In the absence of any real agreement between those engaged in environmental monitoring, initial work was aimed at establishing a standard, low-cost technique for our own work, using a minimum number of sensors in specified locations, to produce sufficient data to reflect accurately the whole environment. This would enable the main engineering questions concerning air mixing and temperature distribution within a given housing system to be answered, so that the biological and economic interpretations could follow.

Sampling frequency and duration

Loggers are capable of frequent scanning over long periods. However, the analysis of the data is costly and it was thought expedient to research the minimum scan

time and period that would give meaningful data to permit comparison of systems under varying climatic conditions.

Results and discussion

ACQUISITION OF DATA

Cage systems

Initially, 36 sensors were used. These were located in three passageways across and four positions along the length of a building, the first and last of these being one bay from each end. The probes were placed at the centre of the passageway at food trough height. Additional sensors were placed at one inlet and one outlet and in a Stevenson's screen outside the building. Analysis of the data has suggested that as few as 18 sensors give only marginally less meaningful data than 36, and this has become our standard procedure (*Figure 16.4*) and has allowed, at times, simultaneous monitoring of two houses at a location, with obvious advantages.

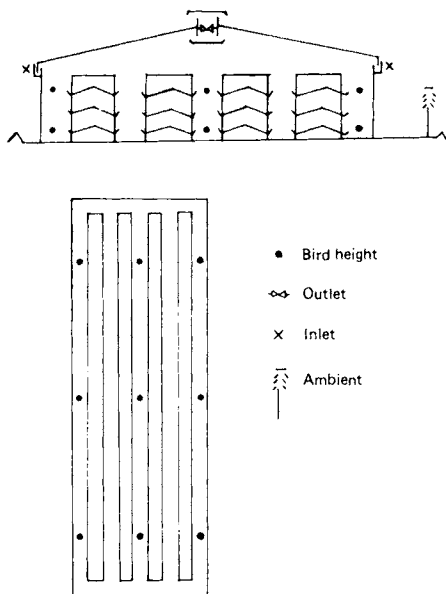


Figure 16.4 Probe positions adopted for monitoring programme

Data from the single inlet probe often did not match the Stevenson's screen information, due to the incoming air picking up the heat from its surroundings, e.g. concrete floors, ventilation hoods, roof sheets. We have therefore standardized on monitoring two inlets, one on either side of the building.

It was thought that the mean outlet temperature would closely match the mean inside temperature. This was found to be generally true, but at times it was significantly lower, indicating 'air slippage' due to inadequacies in the ventilation system. The outlet temperature is of importance in assessing the ventilation system

and our standard therefore is to monitor two outlets. Where automatic controls are used we have found it essential for one probe to be located adjacent to the thermostat to warn of a faulty system or maladjustment.

In order to permit the calculation of temperature lift we need to have an accurate record of ambient temperature, and the standard meteorological Stevenson's screen is used. It is, however, cumbersome for other than long-term monitoring and the more convenient, but more expensive, aspirated thermal screen is now standard in our monitoring exercise.

In our initial runs the lowest scan frequency was 15 min. Analysis of the data indicated that hourly intervals were adequate for an engineering assessment.

Field evidence suggests that many current ventilation systems function satisfactorily, except during periods of unstable or rapidly changing and extreme temperature and pressure conditions. Our objective is to capture data at these times which challenge the ability of the ventilation system to maintain control of the microclimate, so that comparisons and improvements to design can be made.

Initially, periods up to 8 weeks were used, but it was soon clear that even with such long periods the chance of achieving our objective was slight and a decision was made, in consultation with our meteorology colleagues, to standardize on the 14-day period, the data from which would not be an embarrassingly large amount for handling, and to install sensors on a semi-permanent basis, monitoring only when the predicted weather conditions were appropriate to the exercise. In this way, for the expenditure of more than one set of probes per logger, more opportunities could be monitored, thus making greater use of the most expensive resources of manpower and loggers. This is now standard and has been found in practice to be entirely satisfactory. One location has had 36 probes installed for some 2½ years without practical difficulties, in spite of long periods of inactivity.

Floor systems

Sensors are hung at bird height, approximately 500 mm above the litter, to avoid the necessity of protecting the probes. A block of four rows of sensors across the

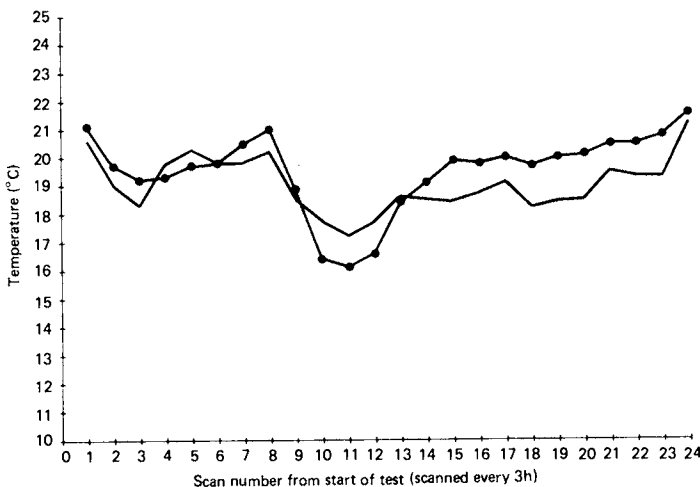


Figure 16.5 Example of poor control and significant end-to-end temperature gradients in a poultry house. ●—●—● = near end; — = far end

Table 16.1 EXAMPLES OF THERMAL PERFORMANCE OF POULTRY HOUSES

<i>Class of stock</i>	<i>Ventilation system</i>	<i>Time of year</i>	<i>Slope*</i>	<i>SD* (°C)</i>
Layers	Conventional	March	0.71	3.39
	Glass fibre ceiling	April	0.02	0.51
	Natural	May	0.79	2.76
	High-speed jet	May	0.26	1.27
Broilers	Conventional	May	0.22	3.03
	Conventional	June	0.57	2.50
	High-speed jet	Sept.	0.28	1.93
	Natural	Sept.	0.04	0.80

*The tabulated figures of merit for the control of the house temperatures are the slope of the linear regression of inside temperature on outside temperature (slope) and the standard deviation of the house temperature about the mean value (SD)

building and six rows along the length cover an area at least equal to the square of the building width. In addition, data are also collected from the two inlets and two outlets and from the Stevenson's screen. To pick up any end-to-end gradient one probe is used at each end of the building (*Figure 16.5*).

Table 16.1 gives the results from a sample of houses and shows a considerable variation in thermal performance. *Figure 16.6* shows a typical graph of temperature *versus* time for representative well-controlled and poorly controlled houses, the latter due to faulty control equipment.

Very often, the circumstantial field evidence, in the absence of any wind data, suggested that wind interference was a major cause of poor performance. *Figures 16.5 and 16.7* show this effect on temperature distribution over a 24h period in a house with fixed outlet openings and without any backdraught valves or other control. In *Figure 16.7*, the effect on vertical temperature distribution is shown clearly.

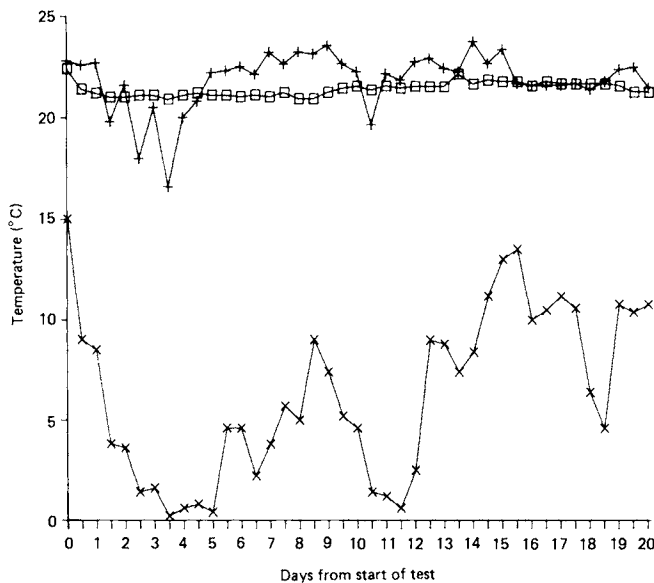


Figure 16.6 Hourly average temperatures inside a poorly controlled poultry house (+), a well controlled poultry house (□) and outside (×)

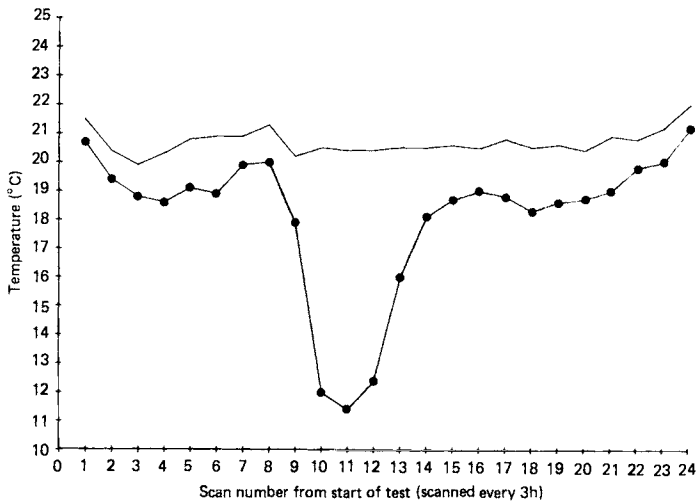


Figure 16.7 Example of poor vertical temperature distribution in a poultry house, possibly due to wind interference. ●—● = lower probes; — = upper probes

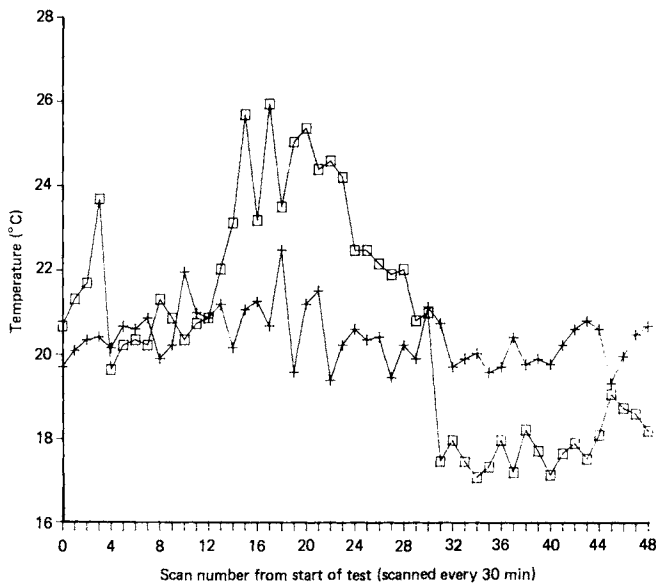


Figure 16.8 Comparison of hourly mean temperatures in poultry houses controlled by hand (□) and by automatically controlled (+) natural ventilation

Good manual control of natural ventilation was thought by many to be adequate. *Figure 16.8* shows a comparison between simultaneously monitored manual and automatically controlled natural ventilation, and clearly the evidence is to the contrary. Likewise, it was thought that automatically controlled natural ventilation (ACNV) would not match fan-ventilated systems. *Figure 16.9* shows the data over a 14-day period where a good fan system was monitored simultaneously with a good ACNV system. In this case the ACNV system provided the better control.

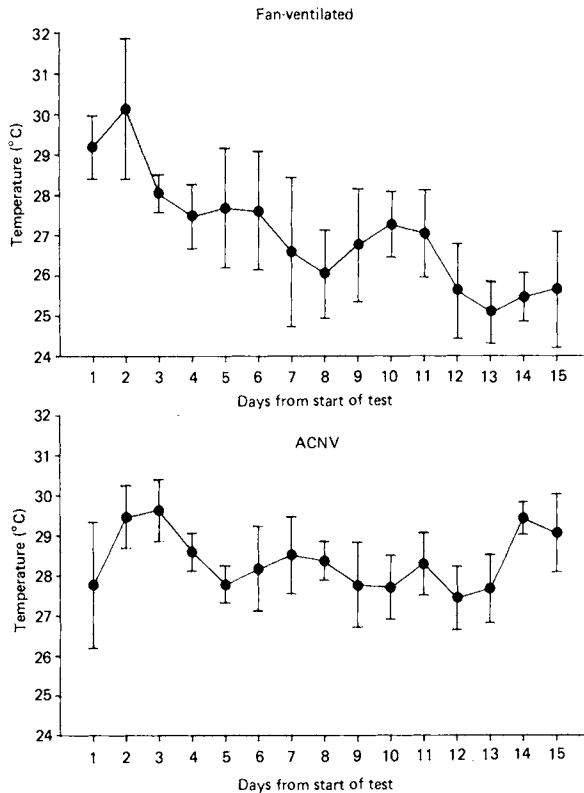


Figure 16.9 Comparison of fan ventilation *versus* ACNV, showing standard deviations about the mean temperatures recorded

Measurements from two floor units monitored during a hot day were used in an attempt to assess the efficiency of reversing the airflow to bring the cooler, incoming air directly on to the stock and disturbing the boundary layer surrounding the stock. This exercise has shown the potential of using the standard deviation over time at individual probes to determine the stability or instability (turbulence) of the air around the probes and, therefore, around the stock. Additionally, by comparing the actual temperature lift against the predicted lift, the efficiency of the ventilation system can be monitored (*Table 16.2*). The reason for the difference in performance in this case appears to be the inadequate design of the high-speed jet system for maximum ventilation throughput and was due to slippage of the incoming air.

Table 16.2 EFFECT OF REVERSING AIR FLOW. A = NORMAL FLOW DIRECTION; B = REVERSE FLOW

Ventilation mode Figure 16.9)		Temperature lift (°C)		Mean temperature (°C)	
		Predicted	Actual	House	Outlet
House 1	A	1.9	4.8	22.1	21.2
	B	2.8	2.7	23.7	24.2
House 2	A	2.9	6.5	24.6	23.3
	B	2.9	2.13	22.6	23.9

Conclusions

The following are some tentative conclusions.

1. The standardization of probe numbers, location, scan time and recording period has given a low-cost method for the description of ventilation systems.
2. Linear regression of inside temperature on outside temperature on an hourly basis over a selected 14-day period gives a very good estimate of system robustness.
3. Use of the standard deviation around the mean temperature of individual probes was a useful guide for assessing control stability.
4. Many of the houses monitored showed design faults that affected temperature distribution at both maximum and minimum air throughput.
5. Automatic control of natural ventilation (ACNV) gave superior temperature distribution to manual control.
6. ACNV can give temperature control as good as that of fan systems.
7. Wind data are an essential part of any description of ventilation systems and future work will include these.

References

- CARPENTER, G.A. (1981). Ventilation systems. In *Environmental Aspects of Housing for Animal Production*. pp. 331–350 Ed. by Clark, J.A. Butterworths, London
- CHARLES, D.R. (1980). Environment for poultry. *Veterinary Record*, **106**, 307–309
- CHARLES, D.R. (1981a). Ventilation for egg production. In *Proceedings, 1st Symposium on Poultry Welfare*. World's Poultry Science Association (Danish Branch)
- CHARLES, D.R. (1981b). Practical ventilation and temperature control for poultry. In *Environmental Aspects of Housing for Animal Production*. pp. 183–196. Ed. by Clark, J.A. Butterworths, London
- CHARLES, D.R. (1984). A model of egg production. *British Poultry Science*, **25**, 309–321
- CHARLES, D.R., SCRAGG, R.H. and BINSTED, J.A. (1981). The effects of temperature on broilers: ventilation rates for the application of temperature control. *British Poultry Science*, **22**, 493–498
- DEATON, J.W., REECE, F.N., LOTT, B.D., KUBENA, L.F. and MAY, J.D. (1972). The efficiency of cooling broilers in summer as measured by growth and feed utilisation. *Poultry Science*, **51**, 69–71
- GRIFFIN, J.G. and VARDAMAN, T.H. (1970). Diurnal cyclic versus daily constant temperatures for broiler performance. *Poultry Science*, **49**, 387–392
- HARRIS, G.C., DODGEN, W.H. and NELSON, G.S. (1974). Effects of diurnally cyclic temperatures on broiler performance. *Poultry Science*, **53**, 2204–2208
- MARSDEN, A. (1981). 'The effect of environmental temperature on energy intake and egg production in the fowl.' Ph.D thesis, University of Reading
- REECE, F.N., DEATON, J.W. and KUBENA, L.F. (1971). Effects of high temperatures and humidity on heat prostration of broiler chickens. In *ASAE Winter Meeting*. American Society of Agricultural Engineers, St Louis
- SIEGEL, H.S. and DRURY, L.N. (1970). Broiler growth in diurnally cycling temperature environments. *Poultry Science*, **49**, 238–244
- SPENCER, P.G. (1973). The problems of controlling poultry-house ventilation. *ADAS Symposium for Housing Manufacturers*

A TECHNIQUE FOR REMOTE MONITORING OF ATMOSPHERIC AMMONIA CONCENTRATIONS IN INTENSIVE POULTRY BUILDINGS, USING A MICROCOMPUTER

P.J. HUNT and C.G. BELYAVIN

Harper Adams Agricultural College, Edgmond, Newport, Shropshire, UK

Introduction

'Controlled environment housing' is widely used in intensive animal production. The poultry industry is considered by many to be the most intensive sector of agriculture, with the majority of eggs being produced by hens in battery cages and most table poultry (broilers) being grown in windowless houses. In all cases the stocking density employed is high and the emphasis is on the efficient conversion of feed into product (eggs or meat). The major factor in determining the efficiency of feed conversion for poultry is the house temperature for the stock (Penderson, 1971). Failure to achieve the desired house temperature results in increased feed usage without increased production, and therefore in lower financial returns.

When house temperatures are below the optimum for production, ventilation is required only to maintain a 'healthy atmosphere'. Charles (1980a) defined the minimum ventilation rate as the rate of air change which prevents the atmospheric carbon dioxide concentration exceeding 0.5% and the ammonia concentration exceeding 25 ppm. Data recorded by Mousley and Fryer (1980) show that, of these contaminants, ammonia is most likely to become a problem in houses used for growing table chickens (broilers).

Current methods of specifying ventilation rate requirements are based on feed intakes (Charles *et al.*, 1978). Although this approach is acceptable when determining maximum ventilation requirements, it is less valid for minimum ventilation rates. Environmental contaminants are mainly system-dependent rather than concerned with metabolic rate and therefore feed intake. This is particularly true for ammonia, which is produced by the chemical breakdown of litter. Therefore, to reduce ventilation rates and, consequently, energy consumption to a minimum, a technique for remotely monitoring ammonia is necessary.

The present method of measuring ammonia concentration in poultry houses is by Draeger sampling tubes (Charles, 1980b). A known volume of air passed through crystals produces a change of colour related to the atmospheric concentration of ammonia. This technique has severe limitations. Because it is not continuous, it does not provide a means for controlling ventilation rate, or for undertaking investigational work concerned with ammonia concentration.

This chapter describes a technique developed for continuously monitoring ammonia concentration in a poultry house. The technique is based on the use of an

aqueous ammonia probe. The work was carried out at the Harper Adams Poultry Husbandry Experimental Unit in a shed stocked with replacement pullets being grown for subsequent egg production.

Aqueous ammonia probe

The specific ion aqueous ammonia probe offers a reliable and accurate technique for determining ammonia concentrations in aqueous solution. Evans and Partridge (1974) found that the probe had an accuracy of $\pm 4\%$ for concentrations greater than $0.4 \text{ mg } \ell^{-1}$ and that the statistical limit of detection was $0.03 \text{ mg } \ell^{-1}$. For reliable results the solution must be alkaline to ensure that it contains ammonia and not ammonium ions. The probe used in the apparatus described later was manufactured by E.I.L. Ltd (Model 8002-8; Kent Instruments, 1981); it responds to the partial pressure of ammonia in the sample. The gas is transferred across a permeable membrane until the partial pressure in the thin film of filling solution between the glass electrode (pH probe) and the probe membrane equals that in the sample solution. The resultant pH change in this film is measured by the glass electrode and the probe develops a potential related to the partial pressure, and hence the concentration, of the ammonia in the sample solution, given by the equation

$$E = E_0 - S \log_{10} [\text{NH}_3]$$

where $S (=2.3RT/F)$ is the Nernst slope factor, which at 25°C has a value of 0.059, E = probe output, E_0 = potential of reference electrode, R = gas constant, T = absolute temperature, F = Faraday's constant, and $[\text{NH}_3]$ = ammonia concentration.

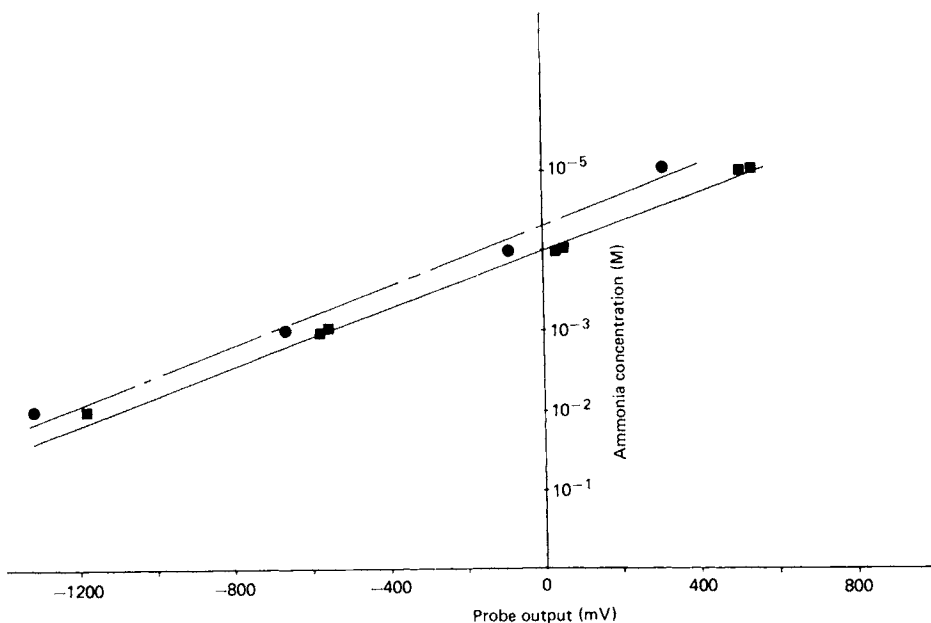


Figure 17.1 Multi-point recalibration of aqueous ammonia probe

CALIBRATION OF THE PROBE

When calibrating the probe it is important to ensure that the temperature and total concentration of dissolved solids in the standard solutions used are close to those for the sample. This was achieved in practice by the addition of sodium chloride to the standard acid and alkali.

A typical set of calibration curves is shown in *Figure 17.1*. The general relation between the ammonia concentration ($[\text{NH}_3]_m$, $\text{mg } \ell^{-1}$) and probe output (v) is given below, where a and b are constants

$$[\text{NH}_3]_m = ae^{bv}$$

Frequent point recalibration of the probe is necessary. During recalibration it is assumed that the slope of the curve remains the same between membrane changes and only the constant a requires updating.

THE MEASUREMENT OF ATMOSPHERIC AMMONIA USING THE PROBE

Before the probe can be used to measure atmospheric ammonia concentration, the ammonia must be in aqueous solution. The atmospheric ammonia to be measured must be absorbed into solution by passing the contaminated air through acid. The very high solubility of ammonia ensures that it dissolves rapidly in acid, forming soluble ammonium salts. This solution must then be made alkaline to liberate ammonia for final determination of the concentration.

A BASIS FOR THE CALCULATION OF ATMOSPHERIC AMMONIA CONCENTRATION USING THE PROBE

Using the aqueous ammonia molar concentration ($[\text{NH}_3]_M$) in the sample solution determined by the probe, the atmospheric concentration can be calculated as follows, where $[\text{NH}_3]_m$ equals the aqueous ammonia concentration ($\text{mg } \ell^{-1}$)

$$[\text{NH}_3]_m = \text{molecular wt ammonia} \times [\text{NH}_3]_M \times 1000$$

$$[\text{NH}_3]_m = 17000 \times [\text{NH}_3]_M$$

From this aqueous ammonia concentration, the atmospheric concentration in ppm can be calculated using the following equation

$$A_m = [\text{NH}_3]_m \times V_s$$

where A_m equals the mass of ammonia in solution (mg) and V_s the volume of solution in litres. By Avogadro's hypothesis, 1 mole of NH_3 gas (17 g) occupies 22.4 ℓ at 273K and an atmospheric pressure of 760mmHg. Atmospheric pressure is assumed to be constant at 760mmHg and if the temperature at the relevant sampling point is $T_p^\circ\text{C}$, then the equivalent volume of ammonia in solution (A_v , litres) can be calculated as follows

$$A_v = \frac{A_m}{17000} \times \frac{22.4 \times (T_p + 273)}{273}$$

$$[\text{NH}_3]_v = \frac{A_v}{V_a} \times 1000000$$

where $[\text{NH}_3]_v$ is the atmospheric ammonia concentration (ppm (v/v)) and V_a is the volume of the air sampled in litres. This can be rewritten as follows

$$[\text{NH}_3]_v = \frac{[\text{NH}_3]_m \times V_s \times (T_p + 273) \times 4.83}{V_a}$$

The ammonia concentration ($[\text{NH}_3]_v$) at the sampling point can be calculated if the sampling point temperature, volume of air pumped and final volume of solution are known.

APPARATUS FOR MEASURING ATMOSPHERIC AMMONIA BASED ON AN AQUEOUS AMMONIA PROBE

Apparatus was developed in an attempt to sample air from the cross-section of a poultry house and to measure the ammonia concentration in the sample. *Figure 17.2* shows a schematic drawing of the measuring apparatus.

An air sample was bubbled through acid contained in the sampling vessel, alkali was then added to the vessel, the sample was stirred and the probe reading recorded.

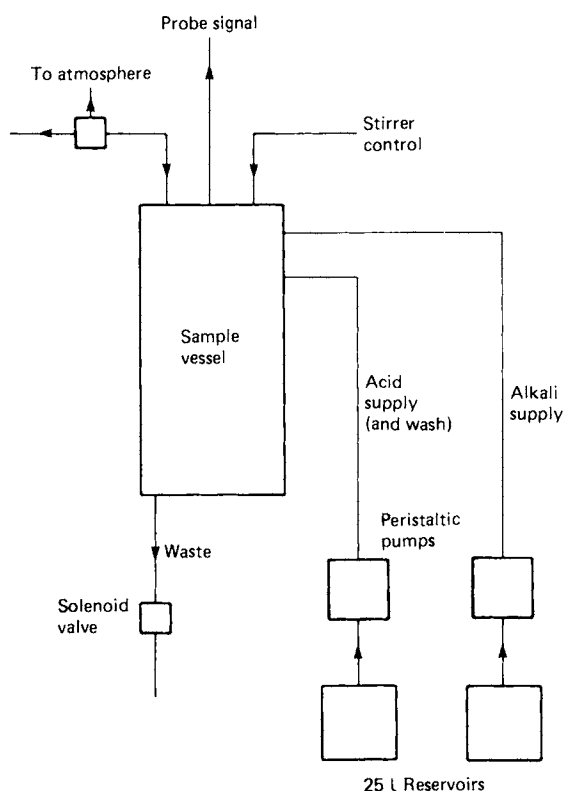


Figure 17.2 Diagrammatic representation of the measuring apparatus

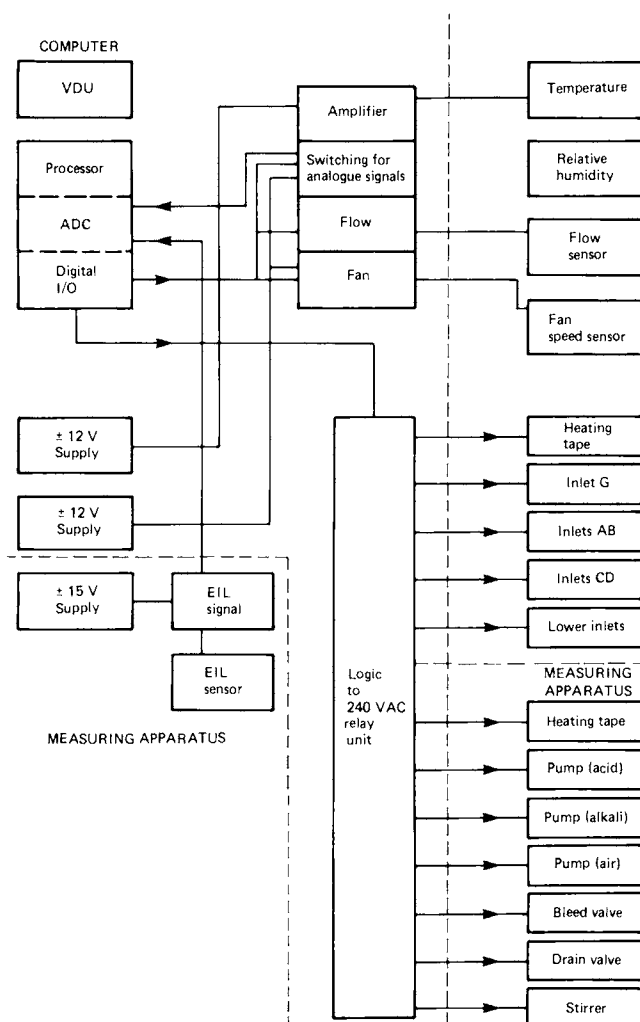


Figure 17.3 Schematic diagram of the layout of the logging and control equipment

The full sequence of operations was controlled by microprocessor and logged using a North Star microcomputer with a Z80A processor and S100 bus and incorporating an analogue-to-digital programmable gain board. Monitoring and control interfaces were developed specifically for this application. A schematic layout of the apparatus is shown in *Figure 17.3*. Sample-point temperature was monitored using AD 590 integrated circuit transducers, the device producing an output current proportional to temperature.

A Capex 2D diaphragm pump was used to obtain the air samples from the house; it had a nominal free air delivery of 7 l min^{-1} . A distribution head was used to ensure complete absorption of the ammonia from the air by the acid. To ensure the sampling tubes were purged prior to bubbling the air sample through the acid, a three-way valve discharged to the atmosphere for a pre-set time. Two peristaltic pumps were used to meter the acid and alkali into the sampling vessel, both with nominal output of 12 l h^{-1} .

The measuring apparatus was located approximately 7.5 m from the sampling points. To ensure that all of the ammonia/air mixture was transferred to the measuring apparatus, the following physical properties of ammonia were considered: (1) ammonia is readily soluble and it is therefore necessary to prevent condensation in the sampling pipework; and (2) ammonia has a relatively small molecular size and will diffuse through plastic materials if a concentration difference exists. To overcome both these potential problems, stainless steel pipe (8 mm o.d.) was used. This was heated (5 W m^{-1}) and insulated. This maintained a temperature difference between the environment and the pipework of approximately $+20^\circ\text{C}$. This temperature lift prevented condensation and reduced the likelihood of ammonia passing through the pipe wall.

Air was sampled from seven points within the house cross-section: three at bird level, three approximately 1.8 m from floor level, and one in the apex of the roof. Inlet filters were fitted to each sampling point.

The air was pumped using a diaphragm pump with stainless steel head and neoprene valves and diaphragms. The pump was calibrated independently for each sampling point to account for varying suction conditions, including filters on the inlet points. The pump was recalibrated frequently and always after removal of the inlet filters.

VOLUMES AND CONCENTRATIONS OF ACID, ALKALI AND AIR

To optimize the performance of the test apparatus, the following variables could be adjusted: (1) the volume ratio of acid to alkali and their relative strengths; (2) the final volume of solution (acid plus alkali); and (3) the volume of air per sample. The factors determining the ratio of acid to alkali were that the final solution must have a pH of at least 11 and total dissolved solids of approximately 0.2M (Kent Instruments, 1981) and that the volume and pH of the acid must be sufficient to ensure maximum removal of the ammonia from the air.

In view of the high solubility of ammonia, it is possible to use a relatively weak acid. Solutions of the following concentrations were used: acid (hydrochloric), pH 6.5, 0.2M dissolved solids; and alkali (sodium hydroxide), pH 11, 0.2M dissolved solids. The acid:alkali ratio used was approximately 2:1. The higher the ratio of air to solution, the greater the concentration of ammonia in the final solution. There were two constraints on the final ratio chosen. First, the ammonia concentration in the solution should be greater than $0.1 \text{ mg } \ell^{-1}$, i.e. approximately 10^{-5} M (Kent Instruments, 1981). To ensure probe outputs in a suitable range, a concentration of approximately $1 \text{ mg } \ell^{-1}$ (about 10^{-4} M) was appropriate. Secondly, the minimum volume of solution was limited by the requirement for sufficient acid to ensure complete absorption of the ammonia. Taking this into account, the minimum volume of solution required was 300 ml.

The equation used to calculate the volume of air required becomes

$$V_a = \frac{[\text{NH}_3]_m \times V_s \times (T_p + 273) \times 4.83}{[\text{NH}_3]_v}$$

If the volume of solution is assumed to be 300 ml and the aqueous ammonia concentration $1 \text{ mg } \ell^{-1}$, and assuming a minimum detectable limit requirement of approximately 15 ppm at a temperature of 20°C , the approximate air volume

required is calculated to be approximately 28 ℓ . This gave an approximate required pumping time of 360s. A pumping time of this length may appear excessive, but it was difficult to reduce it because increasing the pumping rate may lead to ammonia being carried through the acid without being dissolved. In view of the relatively slow changes that occur in ammonia concentration with time in a poultry house, the pumping time of 360s was considered acceptable. The volume of air pumped represented a sphere of effect of the order of 0.2m, compared with a minimum distance between sampling points of approximately 1.8m.

For a higher concentration of ammonia in the atmosphere, lower pumping times and volumes could be used. In terms of ventilation control, it is unlikely that concentrations below 25ppm would be of interest. Therefore, in such cases, the air volume required could be reduced to approximately 17 ℓ and the pumping time to approximately 210s.

Results

Table 17.1 shows the details and times involved in taking a sample of air from the poultry shed and assessing the ammonia contamination using the apparatus described above. Accurate assessment of the performance of the sensing apparatus *in situ* was not possible because of the lack of alternative techniques for monitoring atmospheric ammonia concentration in poultry houses. However, a series of tests was carried out to compare the results from the experimental apparatus with Draeger tube readings. The Draeger tube reading was measured at an inlet point

Table 17.1 TYPICAL TIMINGS FOR THE SEQUENCE OF OPERATIONS IN OBTAINING AN AIR SAMPLE AND MEASURING THE AMMONIA CONCENTRATION IN IT BEFORE USING THE AQUEOUS AMMONIA PROBE

Operation number	Description	Duration (s)
1	Open drain valve of sample vessel, drain previous sample and close valve	50
2	Add acid to flush sample vessel	25
3	Open drain valve of sample vessel, select relevant sampling point and start to pump air from it and expel via bleed valve; drain flushing acid and close drain valve	50
4	Add acid to sample vessel	50
5	Reset the bleed valve, pump from sampling point, bubble through solution in sample vessel and stop pump	300
6	Add alkali	25
7	Stir solution to mix acid and alkali	180
8	Take readings from probe and calculate concentration	30
	Total	710

while the air was being pumped to the sampling apparatus. The results of some of these tests are shown in Table 17.2. The two methods showed good agreement, the difference between the two means being non-significant. Two major reasons for any differences between specific pairs of reading were the difficulty of reading accurately the crystal colour change in the Draeger tube and the difference in time taken to obtain an air sample for the two methods, i.e. with the Draeger approximately 30s and with the sampling apparatus 300s. Taking these factors into account, 'reasonable agreement' could be defined as within ± 5 ppm. Readings that

Table 17.2 COMPARISON BETWEEN MEASUREMENTS MADE AT ONE SAMPLING POINT USING THE AQUEOUS AMMONIA PROBE AND THE DRAEGER APPARATUS

Sample no.	Ammonia concentration (ppm v/v)	
	Aqueous ammonia probe	Draeger apparatus
1	6	7
2	27	28
3	24	27
4	18	10
5	10	8
6	7	7
7	19	12
8	6	9
Mean	14.6	13.5

are outside this band occurred at low concentrations, namely below 15 ppm. This probably reflects the reduced reliability of both techniques at low ammonia concentrations.

ERROR BUDGET FOR MEASUREMENT OF AMMONIA CONCENTRATION USING THE AQUEOUS AMMONIA PROBE

An estimate of likely errors was made by examination of the equation used to estimate the atmospheric ammonia concentration (*see page 221*). This identified the main potential sources of error in determining the atmospheric concentration of ammonia, using the technique described, as: (1) the ammonia concentration in aqueous solution $[\text{NH}_3]_m$; (2) the volume of solution (V_s); (3) the volume of air (V_a); and (4) the air sample temperature (T_p). An analysis of these individual elements in turn allows an estimate of overall accuracy to be made.

Ammonia concentration

The accuracy of the probe output depends on the frequency of recalibration, the reliability of standard solutions, thorough stirring and adequate allowance for response time. The most likely source of error can probably be associated with recalibration. By varying the pumping times it is possible to arrange for the probe reading of ammonia concentration to have a very narrow range (1–5 mg ℓ^{-1}). Frequent point recalibration within this range (10^{-4}M ; approximately 2 mg ℓ^{-1}) reduced this error considerably. Over a 12 h period the maximum variation in voltage output from the probe for a standard concentration of 10^{-4}M was approximately 10 mV. This represented a variation in concentration of approximately 0.09 mg ℓ^{-1} or a maximum error of approximately $\pm 5\%$. The manufacturers claim that the probe should be accurate to within $\pm 2\%$ of concentration. In view of this particular application, an overall error in the probe reading of $\pm 5\%$ would appear to be reasonable.

Volume of solution (V_s)

During calibration of the peristaltic pumps, pump output varied by a maximum of 0.08 ml s^{-1} from the mean, equivalent to a variation of 2%. This represented 6 ml in the total final sample solution of 300 ml.

Volume of air (V_a)

The maximum recorded variation in diaphragm pump output during tests was approximately 3.5%. This was considered reasonable for this type of air pump and, in terms of its overall effect on apparatus accuracy, was considered acceptable.

Sample temperature

The AD 590 temperature transducers used in this study have a claimed repeatability error of less than 0.05°C when properly calibrated. This represented a maximum error of approximately 0.25%. Therefore the contribution to the total error through error in measured sample temperature was small.

Taking these four main sources of error into account, the overall calculated total error of the apparatus was approximately $\pm 10\%$. However, the analysis of the potential sources of the error indicates that overall accuracy should improve with increased atmospheric ammonia concentrations. It would seem reasonable to assume, therefore, that for readings above 25 ppm the apparatus would be accurate to within ± 2 ppm.

TESTS TO DETERMINE THE ACCURACY OF THE APPARATUS

To assess the accuracy of the probe, a series of tests was conducted measuring the output of the probe (mV) when in solutions of known ammonia concentrations. A solution of known ammonia concentration (10^{-4} M) was prepared by dissolving ammonium sulphate (3.3035g) in dilute hydrochloric acid (250ml). Using serial dilution, a final solution with an ammonia concentration of $3.40 \text{ mg } \ell^{-1}$ was produced. Four samples, each of 150ml, were taken. Using the same technique as described above for measuring the ammonia concentration of a sample of air, the accuracy of the probe was tested. The data are summarized in *Table 17.3* where the results obtained with the probe are compared with the calculated concentration of the final solution. The results show that the technique described in this paper for monitoring dissolved ammonia in solution appears to work. The ammonia concentrations of the solutions represent the bottom end of the range in terms of equivalent atmospheric concentration, i.e. 19 ppm.

A series of tests was also carried out to determine the effect of rate of airflow through the apparatus on rate of ammonia recovery. Using a cylinder containing a

Table 17.3 A COMPARISON BETWEEN THE CALCULATED AMMONIA CONCENTRATION OF A SOLUTION AND THE CONCENTRATION MEASURED USING THE PROBE

Sample no.	Ammonia concentration ($\text{mg } \ell^{-1}$)		Difference	% error
	Probe	Actual		
1	3.394	3.400	-0.006	0.17
2	3.548	3.400	+0.048	0.14
3	3.622	3.400	+0.122	3.60
4	3.543	3.400	+0.043	1.30

Table 17.4 RESULTS OF THE MEASUREMENT OF AMMONIA CARRY OVER AT THREE DIFFERENT AIRFLOW RATES

Airflow rate ($\ell \text{ min}^{-1}$)	Equivalent atmospheric ammonia concentration (ppm v/v)	
	Sample vessel	Second vessel
2.4	100	3.6
5.4	100	3.9
10.8	88	5.4

mixture of ammonia and air, three rates of flow were tested. The air was passed through a second vessel containing hydrochloric acid. The equivalent atmospheric concentrations were calculated for each vessel using the probe and the results are summarized in *Table 17.4*. From the results, it can be seen that there is little difference in the quantity of ammonia carried over at the two lower flow rates. The higher carry over at the greater flow rate could decrease the accuracy of the apparatus, but the results show that the flow rate of approximately $5 \ell \text{ min}^{-1}$ selected for the normal operation of the apparatus should not have affected the accuracy.

Summary and conclusions

A method for remotely monitoring atmospheric ammonia concentrations in a poultry house was developed and tested.

The present design of the apparatus limits its application for fan control. The quantities of acid and alkali used (300 ml per sample) and the time taken to measure each sample (approximately 13 min) make the use of the system for control impractical, but as a technique for monitoring ammonia the system has possibilities.

These problems could be reduced considerably if the basic technique were applied to a continuous flow system utilizing the flowthrough head arrangement available with this type of probe. Acid, alkali and house air could be pumped simultaneously. For such an arrangement, the flow could be as low as $3\text{--}5 \text{ ml min}^{-1}$ (Kent Instruments, 1981). Such a system applied to a single sampling point would reduce the volumes of solutions considerably and allow for continuous monitoring.

The problems associated with maintaining the probe, namely replenishing the solutions, changing the membrane and frequent recalibration, would still remain. The ideal solution would be the use of an air probe, but as yet a reliable probe specific to ammonia is not available. The estimated degree of accuracy for the experimental apparatus described would be acceptable for control purposes. This microprocessor-controlled apparatus provides a technique which would be suitable for investigational work on ammonia contamination in livestock buildings and as a method for assessing the performance of alternative devices for measuring atmospheric ammonia concentrations.

Acknowledgements

Financial support from the Agricultural and Food Research Council is gratefully acknowledged, as are the assistance from Mr H.R. Robinson with the design of

computer interfaces and software development and assistance with the chemistry from Dr C.P. Beckwith.

References

- CHARLES, D.R. (1980a). Environment for poultry. *Veterinary Record*, **106**, 307–309
- CHARLES, D.R. (1980b). Ammonia and condensation problems. *ADAS Environment Handout*, No. 12
- CHARLES, D.R., SCRAGG, R., BINSTED, J. and GROOM, C. (1978). *Ventilation Rate, Stocking Density and Temperature for Broilers*. Gleadthorpe Poultry Booklet. London: MAFF
- EVANS, W.H. and PARTRIDGE, B.F. (1974). Determination of ammonia levels in water and waste water with an ammonia probe. *Analyst*, **99**, 367–375
- KENT INSTRUMENTS (1981). *E.I.L. Analytical Instrument Instruction Manual, Model 8002-8 Ammonia Probe*. Gloucester: Kent Industrial Measurements Ltd
- MOULSLEY, L.J. and FRYER, J.T. (1980). 'Broiler house environment.' BSRAE Association Open Day handout
- PENDERSON, J. (1971). What is optimal heat for broilers? *Poultry International*, April, 38–42

ELECTRONIC CONTROLS FOR LIVESTOCK BUILDINGS

J.E. OWEN

University of Reading, UK

Introduction

The developments in electronics and in particular the explosive growth in microprocessor technology over the last 10 years have had a great impact on control techniques in many industries. Whilst there are many exciting opportunities for the application of such technology in agriculture, the industry has been slow to invest in new controls and such controls have not been widely adopted for livestock building applications. This review will therefore be concerned with the discussion of the future possibilities for electronic controls as well as their current use in practice. Furthermore, this discussion will assume that the reader has a basic understanding of what role housing plays in livestock enterprises and that the reader is primarily concerned with the application of control systems rather than the theory, detailed design and engineering of control systems.

Control systems and terms

Considine (1974) fully describes control theory and technology and Cox (1982), in his excellent book, discusses microelectronics in agricultural applications. Therefore, this section will be no more than a brief review of the action of control systems, of their components and of some of the terminology used.

Figure 18.1 illustrates the basic components of an automatic control system, such a system being known as a 'closed-loop' or 'feedback system'. The sensor measures

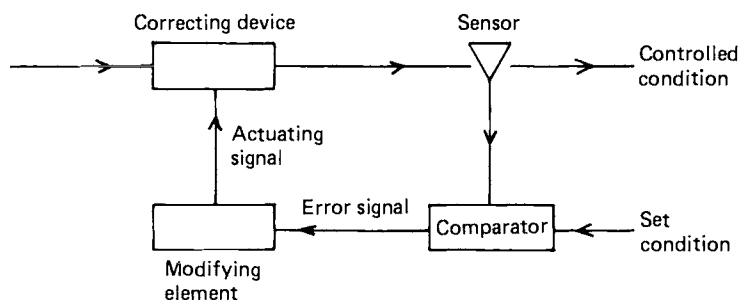


Figure 18.1 Basic features of an automatic control system

the actual state of the controlled condition and produces a signal. This is compared in the 'comparator' with an input signal describing the 'set' or 'desired condition'. Any significant difference between the two will result in an 'error signal'. This error signal will usually need to be modified (amplified or converted) in the 'modifying element'. The modified error signal results in an 'actuating signal' which then initiates some action by the 'corrective device'.

The control system can operate in a number of ways (Hall and Kennedy, 1974) in response to the error signal: it can simply switch the correcting action on or off; it can cause the correcting action to be proportional to the error signal; or it can cause the control action to correspond to some integral or derivative of the error signal. Such responses are used as a basis for the classification of control systems, and systems may incorporate more than one form of response.

If any control system is to work properly it is imperative that the following fundamental criteria are met.

1. The condition to be controlled must be measurable by some sensor.
2. The set or desired condition must be accurately described in the same terms as the sensed condition.
3. The acceptable error must be realistically set, with due regard to the nature of the condition to be controlled and the characteristics of the control system and correcting devices employed. In practice there is bound to be a time lag between the change in a condition and that change being sensed, a time lag before the control system initiates a response, and a further time lag before the correcting device can correct the condition. These time lags can accumulate and the problem of control is to overcome the effects of time lags.
4. The correcting devices employed must have the capacity to perform the tasks required over the range of variation of condition that might occur. If a room requires 10kW of heating to maintain its temperature in cold weather and the heater employed has only 5kW capacity, then no control system, however sophisticated, can maintain the desired temperature when cold weather occurs.
5. The system must be stable in operation.

The stability of systems is often misunderstood and is worth a few words of simple explanation. Control is concerned with correcting some deviation from the desired condition. A positive change in the condition therefore needs a negative correction, i.e. a response in the opposite direction or, in electrical terms, a 180 degree phase shift in the actuating signal. The process and control system may itself cause further phase shifts to occur and if the total phase shift becomes 360 degrees then the corrective action will enhance rather than reduce the deviation from the desired condition. In addition, in the control system there will be a number of energy exchanges. If the energy gained equals the energy lost, then it is said that 'the gain is one'. If more energy is gained than lost then 'the gain is more than one' and so on. These two properties, phase shift and gain, provide a simple yardstick for defining control loop stability: 'A control loop will be stable if, at the frequency of oscillation that gives a total phase shift of 360 degrees around the loop, the gain around the loop is less than one'. Instability will cause the control system to break into endless oscillations.

Electronic control systems require an electrical input; thus, the condition to be controlled must be measured by a sensor or 'transducer' that generates an electrical output. Such devices may respond in an on/off fashion or may give an analogue

output, i.e. an electrical signal which is proportional to the property being monitored. In microprocessor-based control systems, which work on the basis of binary arithmetic, an analogue signal is generally not suitable and it needs to be converted to a digital form in which its magnitude is represented as a set of bits (binary zeros and ones). The microprocessor, working on the basis of cascade digital arithmetic, can then be programmed to carry out a set of instructions, to interpret input signals in the manner required and carry out the appropriate computations, and to output control signals. The program of instructions, or software, while it will need to be converted finally into binary format in order to drive the microprocessor, will probably be written in a high-level language, like BASIC or FORTRAN. Generally, writing programs in a high-level language will prove much less tedious and time-consuming than use of the machine code specific to the particular microprocessor.

A microprocessor cannot be used on its own for control or indeed for any other useful application. It requires input and output elements to communicate with peripheral devices, e.g. sensors. It also requires access to a memory from which instructions can be read, and to which results can be written. The software which directs the operation of all the interconnected electronic components, or hardware, is normally stored in read-only memory (ROM or EPROM). The main feature of this type of memory is that it cannot be corrupted during execution of the program because it can only be read. Data required for the setting up and execution of the program are stored in RAM, i.e. random access memory. RAM allows information to be written in as well as read out, thus stored data can be overwritten and changed at will.

Types of electronic controls

For the purpose of this discussion, electronic controls are divided into three broad categories; these are not necessarily the categories that a control engineer, designer or manufacturer would adopt. The categories are intended to reflect the way the controller appears to the end user or operator.

REPLICATE CONTROLS

These controls simply replicate earlier electrical or mechanical control systems but use electronic circuits rather than the more familiar devices operated on magnetic, thermal expansion, vapour pressure and other such principles. Not only do such controls work in the same manner as their predecessors but they may also replicate the characteristics of electrical or mechanical controls, e.g. differential gap and time constant. Programming of the controller is usually limited to alteration of the set conditions, the operator being provided with manually set function keys or dials built into the controller. The electronics in such controls are usually dedicated to particular tasks and the controllers cannot be used for other purposes. Additionally, since the type of sensors used and their characteristics might have dictated the controller design, the sensor type cannot usually be changed. Typical applications for such controls are as thermostats for heaters, speed controllers for fans, dimmers for lighting, rate or step controllers, and timers.

OPERATOR SELECTABLE MULTIPLE FUNCTION CONTROLS

These controls, primarily because of the limited skills and understanding of operators, also replicate electromechanical devices. They do, however, usually allow the operator to select from a menu of tasks, to change the sequencing of tasks, to alter set conditions, alarm and other limits, and possibly response times. Again, the operator is presented with manually adjustable keys or dials built into the controller. The electronics that replicate electromechanical devices might have the same limitations as applied above. Such controllers may well be micro-processor-based, with software which controls the sequencing and functions selected by the operator. The software itself will, however, not be available for the operator to alter. A number of different peripheral devices, e.g. sensors and relays, might be permissible with the controller. Typical applications are controls for domestic heating systems and 'energy' controllers for small industrial and commercial heating, ventilating and lighting systems.

FULLY PROGRAMMABLE CONTROLS (FPC)

These controls are basically microcomputers, with a number of inputs and outputs to which a range of peripheral devices can be matched, e.g. sensors or actuators. These controls will usually have memory in the form of ROM and RAM; they will have input/output elements and will usually be able to communicate with other recording or monitoring systems. Often a wide variety of sensors can be used and by changing the software it is possible to use the controller for a wide variety of different applications. The controllers will usually be programmed by a specialist employed by the manufacturer, since the control language may be microprocessor-specific and written at machine-code level. However, in large industrial and commercial applications the control programs might be developed by the user, since he will be more familiar with the plant operation and its characteristics. With controllers of this type the basic control strategy can be based on monitored and stored data derived from the system being controlled and the controller might have the capability of 'learning' plant characteristics which were previously unknown. Such characteristics can then be incorporated into control strategy to give improved quality, reliability or economy, i.e. adaptive control. This type of control system is usually found in large industrial or commercial applications. There are also some applications in agriculture where such systems have been used.

Livestock housing applications

There is a vast range of possible applications for electronic controls in livestock buildings; some are so simple that they do not warrant consideration, some so outwith current economic constraints that they are not viable and hence not worthy of lengthy consideration. The discussion in this section will, therefore, concentrate on those applications that, in the author's view, are viable technically and possibly economically at the current time.

Animal identification

In livestock production a number of tasks require animals to be given individual attention, e.g. milking of cows. Other tasks do not have to be carried out on an individual animal basis but if they were there might be economic benefits to be gained, e.g. individual feeding of animals in relation to their production or stage of production. The cost of carrying out these tasks manually is high because they are labour intensive, and there is a commercial interest in automating some of the processes involved.

As a prerequisite to automation there is a need to detect the presence and/or the identity of an individual animal. Determining the presence of an animal is relatively simple; all that may be required is an appropriately located photoelectric cell, limit or proximity switch. Automatic udder washing systems for dairy cows often operate on such simple presence detection (Kingwell, 1980). Since the late 1960s, a variety of electrical devices has been developed for the automatic identification of animals. Initially, passive devices, which incorporated one or more coils tuned to different frequencies, were developed for cattle. Since each device had to have different tuning, each device was unique and was therefore expensive. More recently, devices which can radiate a built-in digital code as a pulse output (effectively a binary output) have been adopted. These can be very cheap if mass produced, can be readily miniaturized to fit into ear tags or under an animal's skin and, if integrated with appropriate sensors, can transmit other information about the animal, e.g. its subcutaneous temperature. Such devices have been widely described (Bridle, 1976; Street, 1979; Cox, 1982; Hansen *et al.*, 1983; Hurst *et al.*, 1983) and require little further description here; their use in various applications will be discussed in the appropriate sections.

Dairy herd management systems

Dairy herd management systems have developed around the need to automate tasks associated with the milking of cows and the need to save labour by increasing the number of cows that can be milked by one man. It has been shown by Clough (1980) that the number of cows milked per man hour can be increased from 100 to 240 by automating the routine tasks. Among these tasks is included the automation of recording of production parameters of individual animals, which is essential for good enterprise management. Because of the need to process and store management data, systems have been built around microcomputers with sufficient capacity to accommodate a wide range of control tasks as well. Many tasks have been only partly automated and still involve input of some production data or control criteria by the operator. A great deal of research and development work has been undertaken, often on a collaborative basis between researchers and manufacturers, and such work has been widely reported. Much of this work will be discussed in other sections because it has more general application. Only those aspects that are confined to dairy cow applications will be discussed in detail here. Among the tasks which such management systems do, or might, control are: animal identification; udder washing, teat cleaning and disinfection; teat cup attachment; milk yield and flow monitoring; milk quality monitoring; control of vacuum during milking; removal and attachment of teat cups; detection of oestrus; feeding both in

and out of parlour; weighing of cows; and birth detection. By no means is control of all of these tasks possible at the present time. Indeed, there are still problems even with those considered to be the simpler tasks, particularly in farm situations. Laycock and Street (1984) identify such problems as being related to the working conditions in parlours, the electrical supply system, the testing of system software and the problems of understanding by cowmen of the operation of the systems.

MILK YIELD AND MILK FLOW

The monitoring of milk flow rate and the yield of individual cows during milking are required for a number of control purposes—milk flow rate for the direct control of automatic removal of the milking cluster when a cow stops ‘giving down’ milk, and milk yield for the future control of feeding to performance of individual cows. Monitoring of the quantity of milk produced by cows has been tackled in a number of ways. The principal methods that have been employed involve measuring the volume or weight of milk in the collecting jar which is incorporated into many pipeline milking systems. The incorporation of strain gauges in the supports of the jar has proved a reliable method for weighing milk (Mundy, 1980; Sobel, Scott and Hoffman, 1980; Horton, 1982). Volume measurement has employed electronic detection of float position in the jar or the photoelectric measurement of milk level in a tube linked to the jar (Schleiter, 1980), which avoids the problem of errors due to froth on the milk surface. Microprocessor controls associated with these systems have been programmed to allow for taring of the jar between the milking of each cow, for the determination of milk flow on the basis of the weight of milk collected over a short time period (Laycock and Street, 1984), and for identifying cows whose yield falls below normal patterns (Mundy, 1980). In-line flow meters, from which a signal (generally in the form of pulses) can be readily integrated over a period to give either flow rate or total yield, have been developed (Cox, 1982; Lettinga, 1983; Ordolff, 1983a) but have not been generally adopted for control applications.

MILK QUALITY

Milk temperature and conductivity may indicate infection of the udder or general ill health in dairy cows (Schlunsen, 1983) and the automation of milk conductivity monitoring has been discussed recently by a number of authors (Maatje *et al.*, 1983; Puckett, Spahr and Rodda, 1983; Spahr *et al.*, 1983). Possible applications for control include automated diversion of suspect milk away from the normal bulk collecting system and automatic diversion of sick animals to treatment areas.

OESTRUS, PREGNANCY AND BIRTH DETECTION

Other monitoring is aimed at the detection of oestrus in dairy cows (Scott *et al.*, 1983; Spahr *et al.*, 1983), the detection of onset of calving and of pregnancy (Scott *et al.*, 1983), and activity monitoring (Thompson, Rodrian and de Vall, 1982). However, use of these for the control of automated processes is probably nowhere near practical application.

CLUSTER REMOVAL AND ATTACHMENT, AND VACUUM CONTROL

Systems for automatic cluster removal are proven in practice and have been widely adopted by farmers. Commercial systems based on milk flow rate monitoring, which remove the milking cluster when the flow rate drops below 0.2 l min^{-1} , have been described (Goldsmith, 1980). During milking the variation in the vacuum to which the cow's teats are subjected is of concern, because it is suspected that this may contribute to the incidence of mastitis. Electronic controls have been utilized to reduce and stabilize the vacuum during milking and to follow programmed changes in vacuum level and pulsation rates as milking proceeds. Currently, automatic cluster attachment is being investigated but it presents a great number of problems in localizing the udder and the teats and in attaching the teat cups (Ordolff, 1983b, 1984). It is a complex problem in robotics which might not be resolved within the economic framework of dairy farming.

Energy saving

The better use of energy derived from fossil fuels is of worldwide concern and microelectronic control systems for many types of energy-saving applications have been developed in all domestic, commercial and industrial sectors. Such systems have not yet been adopted generally in agriculture, although in Britain the energy supply utilities, in particular the Electricity Boards, are promoting energy-saving technology. Their promotion is centred on their self-interest in maximizing the use of their existing distribution networks. However, they appear to be demonstrating cost savings for farmers who can better manage their electrical loads and reduce maximum demand (Mitchell, personal communication). Electronics have contributed to techniques such as 'soft start' of electric motors, and microprocessor-based controls, appropriately programmed, could contribute a great deal to better load management on farms. Although few farmers have invested in such energy management systems, there could be good economic reasons for doing so. The technology exists—it simply needs rational application.

Environmental control

Environmental control is required in housing systems used for livestock that have a quite specific need for temperature control. Pigs and chickens are the two major species of interest, although other farm livestock such as dairy cows, calves, rabbits, ducks and turkeys may also be housed in controlled temperature conditions. In these applications, one is concerned with the control of heat exchange between the animal and its surroundings, which involves air temperature, air speed, the radiant temperatures of the building surfaces, the thermal properties of the floor on which the animal is lying, and air humidity. There is a range of combinations of the vectors mentioned above within which the heat loss from an animal will remain virtually constant. However, researchers have found it more convenient to express most of the thermal vectors as being equivalent to some change in air temperature (Mount, 1975) and the animal's thermal needs as a range of air temperatures lying between a lower (LCT) and an upper critical temperature (UCT) (Close, 1981). In commercial production buildings, environmental control

on a temperature basis is the only currently practical proposition. Indeed, control is generally based on a single set temperature, usually at a value equal to or just above the LCT of the animals housed. Temperature control is generally achieved by the use of variable ventilation with outside air to remove heat (very occasionally air cooling by other means such as evaporative cooling and refrigeration may be used) and conventional heating systems to add heat.

In addition, the air quality in such buildings must be maintained at all times if animal health is to be safeguarded. This is usually done by maintaining some minimum ventilation rate to remove aerial contaminants, although there is a growing interest in other air cleaning methods (see *Waste Disposal and Cleaning Systems*, page 243). The devices to be controlled include fans, various types of actuated baffles, heaters and possibly cooling and air cleaning equipment.

Electronic control systems of the replicate type have been in use since the early 1970s, largely in the form of temperature-based fan speed controllers. The electronics in these controllers meant substituting thermistors for thermal expansion devices as the means of measuring temperature and replacing variable voltage transformers with triacs to reduce fan power input and speed effectively. The initial commercial controllers of this type proved disastrous: they were inaccurate (Barrett, 1975), unreliable, dust- and moisture-prone and, because their designers did not recognize the need to pay attention to the characteristics of fan motors, were likely to cause high voltages to occur on the motor windings, which it was suspected caused 'burn out' problems. Because these controllers were significantly cheaper than their electromechanical equivalents they were widely adopted, caused a lot of livestock problems for producers, and resulted in the whole concept of 'controlled environment' getting a bad name. In recent years much improved replicate type controllers have been developed, offering better accuracy and greater reliability. Newer designs allow users to build up control systems from a range of 'bolt together' function modules (see *Table 18.1*), have

Table 18.1 MANUFACTURER'S RANGE OF COMPATIBLE CONTROL SYSTEM MODULES (BY PERMISSION OF FARM ENERGY AND CONTROL SERVICES LTD)

<i>Module function</i>	<i>Options available</i>
Basic control systems	
Fan speed control	3 or 8 A capacity Minimum speed zero or selectable
Recirculation unit control	8 A capacity
Inlet linear actuator control	24 V AC, 4 actuators
Staged fan control	5 stages
Power boosters	
Auxiliary fan speed control	8 A, same or separate phase
Auxiliary recirculation units	8 A, same or separate phase
Linear actuator expansion	24 V AC, 12 or 24 actuators
Interlocks	
Heater	Single or multi-step, light or heavy duty, gas or electricity
Auxiliary fan	8 A, On/Off
Combined heat and auxiliary fan	As both above
Sensors	
Temperature sensors	Single or multiple sensing
Optional extras	
Digital temperature display	Monitoring and set temperature
Manual override switches	Various
MCB wiring unit	Circuit breakers for overload protection

improved the ease of use for operators, and cater for the severe working environments in which they are installed.

A number of manufacturers have developed control systems of the operator-selectable type which are software-based. Such controllers have allowed for a number of improved features to be more readily incorporated into control systems, e.g. multiple temperature sensing, set temperature profiles over prolonged periods, predictive control action, system commissioning and testing routines, alarm and fail-safe actions. Some of these controllers have allowed communication with a central computer and thus allow central monitoring and recording of controlled condition and controller status. Some controllers allow input of other production data, which can be processed locally or on a central computer for management purposes. There is often considerable debate about the relative merits of central or distributed control. However, in livestock heating and ventilating applications, because of the concern for the animals' health and mortality if failure of centralized control should occur, the general tendency is to use a discrete controller for each animal space.

The fully programmable type of controller has rarely been used in practical livestock environmental control applications, since few producers, or in many instances manufacturers, are capable of writing the software required for the controller and the software cost for individual applications may be prohibitive. In addition, there can be considerable problems when attempting to write software for the control of discrete items of equipment because their operational characteristics, the importance of which was pointed out by Cole (1980), are often unknown or change because of lack of reproducibility in manufactured units (Korslund, 1983). The availability of fully programmable controllers which offer both flexibility and relative ease of program changes has, however, stimulated the development of modes of control previously considered technically too difficult and hence generally economically too expensive. For example, the control of air inlet speed on the basis of measured velocity was always considered impractical; however, Kulp and Hinkle (1984) investigated the use of a microprocessor-based controller for this purpose and suggested that the technique might now be practicable. Cole, McClellan and Mannix (1981) used a programmable controller to produce a linear ventilation response by using speed control of a single fan to smooth out the steps between fan switching. Buckingham and Feilden (1983) described a programmable sequential fan controller which is designed to operate several different sized fans to give improved control of ventilation rate. It can, they suggest, also be programmed to deal with a variety of hybrid ventilation control modes.

Other researchers have recognized the opportunity offered by software-based controllers to incorporate control of many more functions into a single controller, to undertake more complex strategies and to base control on relational or predirectional algorithms and models. Drury and Mitchell (1981) used a microcomputer to run a complex control strategy for a solar poultry brooding system. They reported that this resulted in improved collection of solar energy and reduced consumption of auxiliary heat when compared with a conventional control strategy. Their complex controller, however, required many more inputs than the simpler conventional controller with which it was compared and the difference in use of auxiliary heat could well be explained by the different ventilation strategies employed by the two controllers. Leonard *et al.* (1984) describe work which compared the performance of a minicomputer-based, a microcomputer-based and a thermostat-based control system in a broiler barn. They conclude that control

based on simple algorithms written into the software of the computer-based controllers gave the better control of temperature and ventilation rate and that such control is achievable at a price that is competitive with thermostatic control. Kay and Allison (1983) reported their work on the development of a microprocessor control system for broiler chicken house ventilation. They suggest that the control of ventilation could be based on a control algorithm, itself based on recommended temperatures, temperature reductions coinciding with bird age, maximum relative humidities and static pressure ranges at air inlets. It was envisaged that monitor inputs to the control system would include outside and inside dry-bulb and dew point temperatures, inlet static pressure differences and fan speed. Outputs would control brooder heaters, single and variable speed fans and inlet slot adjustment motors. They calculated that for a typical winter day in Georgia savings of about one third of heating costs might be achieved by ventilating on the basis of controlling moisture rather than adopting a prescribed minimum ventilation rate. By implication, they suggest their controller could achieve such savings. Worley and Allison (1984) further developed the concept of such a controller and described in more detail the equations used in the software. Again, they suggested large energy savings over conventional systems. One must, however, be cautious of such conclusions: first, all the conclusions are based on calculation or simulation; secondly, the controller has not been used in real buildings where the notorious difficulty of measuring dew point temperatures for control purposes could invalidate presumptions about its performance; and thirdly, there is a question whether control of ventilation on a moisture basis will suffice to ensure bird health, which can be influenced by other aerial contaminants such as dust and ammonia.

Boon (1984), in an attempt to compensate for the differing air velocities that can occur over pigs at different ventilation rates, compared the control of temperature for pigs on a variable set temperature (related to air speed) basis with control on a fixed set temperature basis. Using a microcomputer as a fully programmable controller, he used a model (Bruce and Clark, 1979) which was written into the software to calculate the LCT of the housed pigs every 10 min; the calculated LCT then became the target set temperature. The inputs to the model were fixed at the start of the experiment; the novel input was a description of the air velocities over the pigs at different ventilation rates, derived from calibration of the room before the experiments. Boon concluded that variable set temperature (based on calculated LCT) control was better than the fixed set temperature control; both methods were compared with the calculated LCT of the pigs housed. Both controllers maintained the room temperature close to the set temperature, whether fixed or variable. Whilst Boon's effort to give due consideration to the effects of air velocity and to compensate for these is to be applauded, his conclusions seem dubious. He appears to conclude that both controllers did what they were supposed to do, but that because the fixed temperature controller did not do what the variable temperature controller was supposed to do, it was not as good. The most important thing that can be concluded, in practical terms, is that controllers would be improved if they could be operated on the basis of variable temperature; this would compensate for changes in other parameters such as air velocity or radiant temperatures, due to the particular ventilating and heating system being used in a building. Boon's findings also point to the need to monitor variables such as air velocity if models of Bruce and Clarke's type are to be incorporated into control software, since it is difficult to believe that data derived from calibration would apply in real production buildings. Boon's subsequent experiment of employing the

LCT model form of control in practice (Boon, personal communication) would tend to support this view.

One of the major constraints on the development of improved environmental control systems for practical application is the problem of sensors for the variables that might be involved in control decisions. The conditions in which such devices must work are severe, maintenance is minimal and calibration *in situ* not practicable. The continuous measurement of air velocity, relative humidity or wet-bulb temperature, radiant temperature and dust and gas (e.g. CO₂ or NH₃) concentrations, all of which are of interest, is neither economic nor satisfactory at the current time.

Fail safe, alarm and security

Codes relating to animal welfare recommend the use of fail-safe or alarm systems to protect against the death or ill health of animals that can be caused by the failure of automated systems. Farmers are also interested in improving the security of livestock housing to deter intruders. Microelectronic controls for such purposes are readily available. Their low power consumption allows them to be supported by rechargeable batteries in the event of power failure, and they can utilize existing telephone lines for raising the alarm in the homes of stockmen. Software can be written to overcome many of the problems that have deterred farmers from using such systems in the past, e.g. having to get out of bed in the middle of the night because the electrical power supply has failed, only to find it has been reinstated by the time one gets to the animal housing. Clark (1980) has discussed the problems of installing such systems in agricultural situations.

Feeding

The discussion of applications in this sector will be confined to the metering, proportioning and delivery of feed to housed livestock. Control of automated feed preparation (milling and mixing) will not be discussed. Manufactured animal feeds are compounded on the basis of providing the animal's nutrient requirements on a weight basis, and evaluation of farm-grown dietary constituents is also determined on a weight basis. The farmer's objective, therefore, must be to ensure that animals receive the correct weight of feed to meet their needs. Automatic rationing of feed to livestock has, however, generally been on a volumetric basis (feed density being assumed to be constant) or, alternatively, on the basis of a timed delivery of feed (when the mass flow rate is assumed to be constant). Rarely is either of these assumptions correct.

Electronic measurement of the weight of large quantities of feed dispensed from bulk containers is readily achieved by the use of properly installed load cells in the supporting structure. This can be useful if one wants to control the total amount of food being fed to all the animals in a building on a daily basis. There has been particular interest in batch weighing of feed in feed distribution wagons for mixing and distribution purposes, and electronic systems for this purpose have been described by Smith and Dawson (1978), Butterworth and Butterworth (1979) and Bruce, Smith and Meeke (1980). While none of these systems is automatic (all they do is provide the operator with information on which he can act), they could readily

be adapted for control. Indeed, a number of farmers have already started to adopt such systems for the control of feed conveyors from bulk storage bins. The possibility of continuous weighing for use with conveying systems has been investigated and a number of commercial systems are described by Cox (1982). Dawson, Hooper and Ambler (1976) pointed out what they considered to be the advantages of continuous weighers for agricultural purposes and discussed a belt weigher that utilized load cells for weighing forage. Puckett *et al.* (1979) described a programmable controller for feeding both forage and concentrates to dairy cows. The controller could apparently deliver differing quantities and types of feed to a number of selected locations. They referred to earlier work by Hyde *et al.* (1973) which described an automatic feeding system with a different controller incorporating automatic proportioning of concentrates and forage. In this system the concentrate dispenser motor was controlled on the basis of the flow of forage over a belt weigher. It is inferred in the 1979 paper by Puckett that this feature is retained in the newer programmable controller.

In pig and poultry production there are a large number of feeding systems employed, some of which are controlled by conventional electromechanical devices and others by microprocessor-based systems of the replicate or operator-selectable type. Most systems dispense feed to groups of animals, the sow and boar being the only animals that are individually fed in commercial practice. Dry-feed conveying systems are used to fill or top up feed dispensers, and controls usually do little more than switch such systems on and off periodically. Systems which allow rationing of feed to an individual animal usually require some mechanical adjustment to the feed dispenser. Liquid-feed conveying systems generally dispense feed into troughs by opening a valve for a period of time. Such systems might have controls which allow preselection of the time allowed per trough, the number of feeds per day and sequencing of feed dispersal. Often such controls are incorporated into the same control package that controls the preparation of the liquid feed. In most instances electronic controls are of the replicate type. There is an interest in feeding groups of animals on the basis of their weight. However, until the problem of weighing animals *in situ* is resolved (*see Weighing of Animals, page 244*), such systems are unlikely to be economically viable. For growing pigs the need for such systems is likely to disappear anyway, since leaner genetic strains, the reducing number of castrates being reared and the processor's demand for lighter pigs allow *ad libitum* feeding to be practised (Smith, 1982). An alternative approach would be to control the level of feeding on the basis of the predicted weight which could be achieved by incorporating animal growth algorithms in control software. Huizing (1973) described an early mechanical controller designed to operate in such a way for the control of a pig feeding dispenser. The individual rationing of feed to tethered or stalled animals is simple to control, whether it is done manually or automatically. Indeed, its very simplicity was largely responsible for the adoption of stall systems for sows by the pig industry and also led to the in-parlour feeding of loose-housed dairy cows. In groups of animals, the competition between animals at the feeder denies some animals a sufficiency of feed and can reduce productivity while other animals overfeed with no resulting improvement in productivity. Individual feeding systems for cows, which are fitted with identifying transponders, have been developed by commercial companies and their use has been investigated (Pojtner, 1983). Ipema *et al.* (1983) reported on their development of an automatic feeding system for dispensing small portions (500g) of forage to dairy cows from a restricted number of feeding stations. The system employs a computer and a

microcomputer sequential controller with inputs from the existing animal identification system, from various contactless proximity switches and from a strain-gauge weigher. The system can feed individual animals predetermined amounts of feed and numbers of feeds in a certain time. Production response and behaviour studies were also carried out, this aspect being most important, as is pointed out by Pirkelmann (1983), since the control and automation of feeding systems must not reduce the productivity of the animals.

In Britain the use of animal identification for controlling the individual feeding of sows kept in large groups (30 plus) is currently being investigated so that producers can comply with the recommendations of welfare codes. In such systems the design of the feed stations and the behaviour of the sows appears to raise more problems than the control systems and animal identification.

Current investigations in Britain with veal calves fitted with transponders for the control of a restricted automatic feeding system indicate improvements in feed conversion for the restricted feeding system when compared with *ad libitum* mechanized feeding.

Commercially available automated individual feeding systems are almost all microprocessor-controlled and vary in complexity of control operation. Early systems simply opened a gate to allow a particular animal, identified by its individual transponder, access to a feed station. Other systems only dispense feed to an animal once in some predetermined period. If the animal returns again within that period then no feed will be dispensed. More complex systems allow the operator to preselect the quantity and number of feeds allowed to any animal, can record the daily feed consumption of each cow, and might both compensate for and draw attention to underconsumption of feed by an individual animal.

Health and other factors

The monitoring of health in dairy cows has already been discussed. There is also interest in the monitoring of such factors in other animals. Electronic means of measuring variables such as backfat thickness in pigs (Miles and Fursey, 1974) and lambs (Gooden, Beach and Pudchas, 1980), percentage of fat in the body of cattle (Miles, Fursey and Woods, 1981), and temperature, respiration rate and heartbeat in chickens (Mitchell, 1977) have been developed. They have not yet been used for automatic control purposes.

Waste disposal and cleaning systems

The control of fully automated waste disposal systems is generally confined to sequencing of operations. Although microprocessor controls may be used for such tasks they are usually simple replicate or operator-selectable types; they involve little more than the monitoring of level, position or force (using standard industrial techniques) for feedback control purposes. Systems used for the final disposal, treatment or utilization of wastes will also require controls, but these are outside the scope of this discussion. Details of the general requirements of such systems are to be found in a number of sources (e.g. Animal Manure Management Committee, 1979; Midwest Plan Service, 1979). Sinclair (1980) discusses the special needs for cleaning in dairy farming, where milking equipment must be cleaned to meet

particular recommended standards (BSI, 1975). Again, controls will do little more than sequence the cleaning operations.

Air cleaning is becoming of more importance, both cleaning of the air within buildings in order to reduce the levels of contaminants to which housed animals are exposed and cleaning of the air exhausted from buildings, because of the growing concern for the pollution by dust and smell of the surrounding locality. At present, there are few quantitative means of measuring either dust or gas concentrations, smell or the components of smell, which could be used for control of air cleaning systems in practical farm situations (Leonard and McQuitty, 1982). Certainly, air filtration systems are technically possible; whether they are economically viable remains to be proven. There are indications that air filtration could benefit animal health (Pritchard *et al.*, 1981) and that simple filtration systems could be provided at a reasonable capital and running cost (Owen, 1982a,b). Other techniques such as air washing have been investigated (Jongebreur and Van Geelen, 1974) and offer possible solutions to the removal of smell. Experience suggests that farm workers are not prepared to give such systems the regular attention and maintenance required for their successful operation; therefore, automatic control will almost certainly be required if they are to be adopted by farmers.

Weighing of animals

The chore of weighing the animals in pig herds has meant that the job is done on most farms only when absolutely necessary. The development of a pig weighing system by Smith and Turner (1974) has resulted in the availability of a microprocessor-controlled system which, on the basis of the integration and averaging of the output from load cells over several seconds, can not only give a reading of animal weight but can also spray a marker onto those pigs that exceed some preselected weight. The automated feeding of dairy cows can be based on both the body weight of the dairy cow and its milk yield. Filby, Turner and Street (1979) described a walk-through weighing system which has been incorporated in an automated dairy herd management system and had proved to be reliable in use (Laycock and Street, 1984). The feeding of broiler chickens could be undertaken on the basis of mean flock weight and a system has been developed, based on a strain-gauged perch and a microcomputer, which can estimate the mean weight to within about 2.5%, provided that sufficient birds in the flock use the perch (Turner *et al.*, 1984).

This last example is of interest because it is the first development of a weighing system which can weigh groups of animals *in situ* without requiring humans to move the animals. Such weighing techniques could contribute to the automation of many activities, other than feeding, which are animal weight-related; for example selection of environmental parameters such as minimum ventilation rate or temperature, control of movement of animals to loading pens or to new accommodation, control of space allowance by changes of pen size or allowing access to more space, and control of rate of waste disposal by the frequency of slurry channel flushing.

Any regular weighing of animals will reveal day-to-day changes in the animals' weight, and one of the major problems for control purposes is the interpretation of the monitored data. The decisions as to what are significant changes and trends or which are incorrect data (because two animals are on the weighing device at the

same time) require careful appraisal before control decisions based on such data are executed.

On-farm problems associated with electronic controls

Many of the problems associated with the use of electronic controls on the farm are exactly the same as those encountered in other industries. Microprocessor malfunction in other industries is discussed by Birtles and Smith (1985). Problems in farm situations can be conveniently considered under four broad headings.

WORKING CONDITIONS

The working environment for all types of equipment on farms is hostile. Exposures to water (often from a pressure hose), faeces, silage effluent, dusts, gases (possibly in solution), agricultural chemicals and animals (including vermin) are common. Corrosion may cause the failure of sensors, connectors, printed circuit boards and other components. Moisture and dust ingress into controller enclosures and vermin attacks on wiring systems lead to short circuiting. Dust on sensors and actuating devices causes a variety of problems such as overheating, jamming and imbalancing, which can result in failure. Many of the problems can be solved by the suitable siting of controls, others by good design and proper specification, e.g. by selection of suitable enclosures for controllers; by minimizing the number of holes through which dust or moisture can enter enclosures; by provision of seals and glands at entry points to enclosures; by specifying suitably protected wiring systems; by selection of suitable connectors and by total encapsulation of circuits in suitable compounds. If in doubt, the manufacturer can consult international and national standards which give guidance on the selection and specification of components. A high level of protection can only be achieved at a cost, however, and one of the major problems for manufacturers is the cost constraint imposed by the farmer, who rarely compares competing products on the basis of their specification.

COMPONENTS AND ELECTROMAGNETIC INTERFERENCE

Most microelectronic circuits, if they are going to fail, will do so during their initial period of operation. This is usually due to the imperfection or malfunction of the mass-produced electronic components that are used. Subsequently, failure will inevitably be caused by some external influence. Because the failure of electronic components will generally be associated with high operating temperatures, many manufacturers will test their controllers for an initial period, known as 'burn in', at temperatures above the normal operating temperature. This minimizes the incidence of failure in operation and consequently microelectronic controllers are much more reliable than other types.

Microprocessor controllers can be sensitive to external electromagnetic interference, known as 'noise', which results in the controller's receiving corrupt information via its input wiring. Such noise derives from a variety of external sources; it may be picked up by the controller or its associated wiring at radio

frequencies, or may be superimposed on the incoming power supply as spikes, surges and dips. Such interference can be reduced by screening, filtering and low-impedance earthing, but very often the noise is site-specific and can cause major problems. Again, standards of various types exist which can help in the selection of appropriate components and methods for the suppression of electromagnetic interference.

SOFTWARE

Some of the problems associated with the writing of software have already been mentioned, there are also problems which relate to its testing and cost. Software writing is a highly skilled job. For control purposes the author requires an understanding of the control task, the external influences that make control necessary, the likely effects on the controlled condition, the mathematics of control, and the characteristics of the sensors and correcting devices being used. Often the information he requires is not available, e.g. time constants of correcting devices, and much of the information may be quite specific to the individual control problem. The software may have to be developed and improved over a period of time as the control system's operational characteristics are learned in practice. Of course, errors may occur when writing the software and these have to be traced and corrected, a process known as 'debugging'. Because it can prove difficult to decide whether a problem that may arise is caused by a fault in the software or a misinterpretation of some characteristic, many authors write into software self-test routines which allow rapid debugging. The work involved is costly, and if this cost cannot be recovered by a controller's having wide application, then the final price to the customer might be prohibitive. To overcome this problem, one manufacturer (Farm Energy and Control Services Ltd, personal communication) is engaged in a project ('DICAM') which is aimed at developing controllers capable of being interfaced with almost any sensor or correcting device, of communicating with other central computers, and of learning the operational characteristics associated with the control problem (*Table 18.1*). Projects like DICAM could reduce software costs to a level which does not inhibit the use of software-based controllers for individual control problems.

OPERATOR'S UNDERSTANDING

Finally, one of the biggest problems associated with the use of electronic controls in livestock enterprises is the lack of understanding by the stockman of how the controls operate or of how they should be set. This is not a problem restricted to farms: Crawshaw (1984) reported a study of the behaviour and understanding of consumers using simple domestic heating controls. She found a total lack of understanding and confusion about both the purpose and operation of controls as simple as time switches and thermostats for central heating boilers. Crawshaw highlights the need for better instructions and labelling and the provision of cues to which the customer can respond. She concludes by saying:

... designers should design for users, and provide them with systems they can understand and control. To do this they must bear in mind that user-perceptions are qualitatively different from their own and user-understandings are not necessarily based on the logic of science. They must therefore design to new criteria based on *user* research.

This seems to be the challenge for the future, because with the technology now available there are few constraints on making the controls, in computer jargon, 'user friendly'.

References

- ANIMAL MANURE MANAGEMENT COMMITTEE (1979). *Canada Animal Manure Management Guide*. Publication 1534. Agriculture Canada, Ottawa
- BARRETT, M. (1975). Controlled environment—is there such a thing? *Power Farming*, October, 25–27
- BIRTLES, A.B. and SMITH, G.P. (1985). Microprocessor malfunctions in building services. *Heat and Air Conditioning Journal*, **55** (635), 13–15
- BOON, C.R. (1984). The control of climatic environment for finishing pigs using Lower Critical Temperature. *Journal of Agricultural Engineering Research*, **29**, 295–303
- BRIDLE, J.E. (1976). Automatic dairy cow identification. *Journal of Agricultural Engineering Research*, **21**, 41–48
- BRUCE, D.M., SMITH, R.A. and MEEKE, I.R. (1980). Mobile feeding equipment—a weighing unit with auto taring and batching facilities. *Journal of Agricultural Engineering Research*, **25**, 155–160
- BRUCE, J.M. and CLARK, J.J. (1979). Models of heat production and critical temperature for growing pigs. *Animal Production*, **28**, 353–369
- BSI (1975). *B.S. 5226. Recommendations for the Cleaning and Sterilization of Pipeline Milking Machine Installations*. British Standards Institution, London
- BUCKINGHAM, J.E. and FEILDEN, N.E.H. (1983). A programmed sequential fan controller. *Farm Building Progress*, **72**, 19–22
- BUTTERWORTH, H.M. and BUTTERWORTH, W.R. (1979). 'Computer read-outs for feed mixer trailers.' ASAE Paper, No. 79-1071. American Society of Agricultural Engineers, St Joseph, Michigan
- CLARK, S.A. (1980). 'Agricultural alarm systems'. ASAE Paper, No. 80-3524. American Society of Agricultural Engineers, St Joseph, Michigan
- CLOSE, W.H. (1981). The climatic requirements of the pig. In *Environmental Aspects of Housing for Animal Production*. pp. 149–166. Ed. by Clark, J.A. Butterworths, London
- CLOUGH, P.A. (1980). The effect of mechanization and automation on machine milking performance in milking parlours. In *The Mechanisation and Automation of Cattle Production*. pp. 97–101. Ed. by Dodd, F.H. British Society for Animal Production, Reading
- COLE, G.W. (1980). The application of control systems theory to the analysis of ventilated animal housing environments. *Transactions of the American Society of Agricultural Engineers*, **23**, 431–436
- COLE, G.W., MCCLELLAN, P.W. and MANNIX, J.G. (1981). A linear ventilation rate temperature controller for a confined animal housing system. *Transactions of the American Society of Agricultural Engineers*, **24**, 706–710
- CONSIDINE, D.M. (1974). (Ed.) *Process Instruments and Controls Handbook*. McGraw-Hill, New York
- COX, S.W.R. (1982). *Microelectronics in Agriculture and Horticulture*. Granada, London
- CRAWSHAW, A.J.E. (1984). 'Consumer behaviour and domestic energy use'. Ergonomics Research Group, University of Hull

- DAWSON, J.R., HOOPER, A.W. and AMBLER, B. (1976). A continuous weigher for agricultural use. *Journal of Agricultural Engineering Research*, **21**, 389–397
- DRURY, L.N. and MITCHELL, B.W. (1981). 'Solar poultry brooding system performance with microcomputer control strategy versus conventional control'. ASAE Paper, No. 81-4556. American Society of Agricultural Engineers, St Joseph, Michigan
- FILBY, D.E., TURNER, M.J.B. and STREET, M.J. (1979). A walk through weigher for dairy cows. *Journal of Agricultural Engineering Research*, **24**, 67–78
- GOLDSMITH, F.E. (1980). Automatic teatcup cluster removal. In *The Mechanisation and Automation of Cattle Production*. pp. 71–80. Ed. by Dodd, F.H. British Society for Animal Production, Reading
- GOODEN, J.M., BEACH, A.D. and PUDCHAS, R.W. (1980). Measurement of sub-cutaneous back fat depth in live lambs with an ultrasonic probe. *New Zealand Journal of Agricultural Engineering Research*, **23**, 161–165
- HALL, G.A. and KENNEDY, R.H. (1974). Fundamentals of automatic process control. In *Process Instruments and Controls Handbook*. pp. 18(18)–18(29). Ed. by Considine, D.M. McGraw-Hill, New York
- HANSEN, L.L., HAGELSO, A.M., NORTHEVED, A., NILSSON, O., JENSEN, J.W. and STAUN, H. (1983). Electronic identification and monitoring of behavioural, physiological and performance criteria as aid to control future pig and cattle production and secure animal welfare. In *Proceedings, Symposium on Automation in Dairying*, pp. 19–26. Instituut voor Mechanisatie, Arbeid en Gebouwen, Wageningen
- HORTON, C.D. (1982). *Development of Milk Yield Recording System using Strain Gauged Beam to Weigh the Milk*. Divisional note DN 1132, National Institute of Agricultural Engineering, Silsoe
- HUIZING, J.A. (1973). Pig feeding in the Netherlands. (Proceedings of the subject day on livestock feeding and weighing.) *NIAE Reports*, No. 11, National Institute of Agricultural Engineering, Silsoe
- HURST, G.C., HAMMOND, K., MCINTOSH, A.I., YERBURY, M.J., DAVIES, L.W., DAVIES, J.W., WEBB, R.F. and COOPER, D.N. (1983). Overcoming the problems of identifying and recording livestock under extensive management. In *Proceedings, Symposium on Automation in Dairying*, pp. 27–32. Instituut voor Mechanisatie, Arbeid en Gebouwen, Wageningen
- HYDE, G.M., PUCKETT, H.B., OLIVER, E.F. and HARSHBARGER, K.E. (1973). Designing an automatic forage and concentrate proportioning system. *Transactions of the American Society of Agricultural Engineers*, **16**, 109–111
- IPEMA, A.H., ROSSING, W., CORNELISSEN, J.G. and JANSSEN, T. (1983). A system for the individual dispensing of forage. In *Proceedings, Symposium on Automation in Dairying*, pp. 43–60. Instituut voor Mechanisatie, Arbeid en Gebouwen, Wageningen
- JONGEBREUR, A.A. and VAN GEELLEN, M.A. (1974). *Befrijding van door ventilatielucht veroorzaakte stankhinder*. [Abating the nuisance by smell caused by ventilation air.] Publication No. 63. Instituut voor Landbouwbedrijfsgehouwen, Mansholtlaan 12, Wageningen, Netherlands
- KAY, F.W. and ALLISON, J.M. (1983). Microprocessor control of broiler house ventilation. ASAE Paper, No. 83-3029. American Society of Agricultural Engineers, St Joseph, Michigan
- KINGWELL, R.G. (1980). Udder washing and teat disinfection. In *The Mechanisation and Automation of Cattle Production*. pp. 65–70. Ed. by Dodd, F.H. British Society for Animal Production, Reading
- KORSLUND, D.J. (1983). 'Microprocessor-based control for phase modulation of

- fans'. ASAE Paper, No. 83-3030. American Society of Agricultural Engineers, St Joseph, Michigan
- KULP, J.B. and HINKLE, C.N. (1984). Animal shelter inlet air velocity control with a microprocessor. In *Agricultural Electronics—1983 and Beyond*. Vol. 2. *Controlled Environments, Livestock Production Systems, Materials Handling and Processing*. pp. 351–355. American Society of Agricultural Engineers, St Joseph, Michigan
- LAYCOCK, C.L. and STREET, M.J. (1984). Development and use of an automated management system for a large dairy herd. *Journal of Agricultural Engineering Research*, **30**, 265–273
- LEONARD, J.J., FEDDES, J.J.R., CLARK, P.C. and MCQUITTY, J.B. (1984). Mini- and micro-computer control of the environment in a broiler barn. In *Agricultural Electronics—1983 and Beyond*. Vol. 2. *Controlled Environments, Livestock Production Systems, Materials Handling and Processing*. pp. 360–369. American Society of Agricultural Engineers, St Joseph, Michigan
- LEONARD, J.J. and MCQUITTY, J.B. (1982). 'A review of automation and automatic control applied to intensive animal production'. ASAE Paper, No. 82-310. American Society of Agricultural Engineers, St Joseph, Michigan
- LETTINGA, J. (1983). Design of an in line milkmeter with sampling device. In *Proceedings, Symposium on Automation in Dairying*, pp. 153–162. Instituut voor Mechanisatie, Arbeid en Gebouwen, Wageningen
- MAATJE, K., ROSSING, W., GARSEN, G.J. and PLUIJGERS, H.G. (1983). Automation of electrical conductivity measurements during milking. In *Proceedings, Symposium on Automation in Dairying*, pp. 89–100. Instituut voor Mechanisatie, Arbeid en Gebouwen, Wageningen
- MIDWEST PLAN SERVICE (1979). *Livestock Waste Facilities Handbook*. 94 pp. Midwest Plan Service, Ames, Iowa
- MILES, C.A. and FURSEY, G.A.J. (1974). A note on the velocity of ultrasound in living tissue. *Animal Production*, **18**, 93–96
- MILES, C.A., FURSEY, G.A.J. and WOODS, M.O. (1981). Physical measurement of meat composition. *Biennial Reports of the Meat Research Institute*, 1981, 41–43
- MITCHELL, B.W. (1977). Multiple antenna telemetry system for physiological measurements. *Transactions of the American Society of Agricultural Engineers*, **20**, 741–744
- MOUNT, L.E. (1975). The assessment of thermal environment in relation to pig production. *Livestock Production Science*, **2**, 381–392
- MUNDY, E.J. (1980). Electronics and the Bridget's dairy herd. *Agricultural Engineer*, **35**, 38–39
- ORDOLFF, D. (1983a). Milk yield recording with continuous milkflow. In *Proceedings, Symposium on Automation in Dairying*. pp. 149–152. Instituut voor Mechanisatie, Arbeid en Gebouwen, Wageningen
- ORDOLFF, D. (1983b). Investigations on a system for automatic teat cup attaching. In *Proceedings, Symposium on Automation in Dairying*. pp. 287–290. Instituut voor Mechanisatie, Arbeid en Gebouwen, Wageningen
- ORDOLFF, D. (1984). A system for automatic teat-cup attachment. *Journal of Agricultural Engineering Research*, **30**, 65–70
- OWEN, J.E. (1982a). Dust-filtration solutions and their cost. *Farm Building Progress*, **68**, 19–23
- OWEN, J.E. (1982b). The influence of buildings on respiratory disease. *Pig Veterinary Society Proceedings*, **9**, 24–35
- PIRKELMANN, H. (1983). Technical and biological factors for automated feeding of

- dairy cows. In *Proceedings, Symposium on Automation in Dairying*. pp. 61–68. Instituut voor Mechanisatie, Arbeid en Gebouwen, Wageningen
- POJNER, M. (1983). Adaptation, compound feed intake and milk production of dairy cows fed by means of alfa-feed automatic feeders. In *Proceedings, Symposium on Automation in Dairying*. pp. 33–42. Instituut voor Mechanisatie, Arbeid en Gebouwen, Wageningen
- PRITCHARD, D.G., CARPENTER, G.A., MORZANA, S.P., HARKNESS, J.W., RICHARDS, M.S. and BREWER, J.I. (1981). Effective air filtration on respiratory disease in intensively housed veal calves. *Veterinary Record*, **109**, 5–9
- PUCKETT, H.B., OLIVER, E.F., HARSHBARGER, K.E. and HINDS, F.C. (1979). Programmable controllers for livestock feeding systems. *Transactions of the American Society of Agricultural Engineers*, **22**, 170–173
- PUCKETT, H.B., SPAHR, S.L. and RODDA, E.D. (1983). Real-time measurement of milk conductivity. In *Proceedings, Symposium on Automation in Dairying*. pp. 101–114. Instituut voor Mechanisatie, Arbeid en Gebouwen, Wageningen
- SCHLETER, P. (1980). *Milk Meter*. German Federal Republic Patent Application No 2 839 101
- SCHLUNSEN, D. (1983). Validity of different physiological parameters for automatic control of the udder health. In *Proceedings, Symposium on Automation in Dairying*. pp. 69–78. Instituut voor Mechanisatie, Arbeid en Gebouwen, Wageningen
- SCOTT, N.R., SIGRIMIS, N.A., SOBEL, A.T., MARSHALL, R.A. and HENKE, D.V. (1983). Electronic developments in dairy herd management. In *Proceedings, Symposium on Automation in Dairying*. pp. 221–236. Instituut voor Mechanisatie, Arbeid en Gebouwen, Wageningen
- SINCLAIR, G. (1980). Cleaning milking machines, bulk tanks, yards and milking parlours. In *The Mechanisation and Automation of Cattle Production*. pp. 81–95. Ed. by Dodd, F.H. British Society of Animal Production, Reading
- SMITH, A.T. (1982). Housing and feeding systems — pigs. *Agricultural Engineer*, **37**, 44–48
- SMITH, R.A. and DAWSON, J.R. (1978). A near-weight indicator for mobile feeding equipment. *Journal of Agricultural Engineering Research*, **23**, 105–107
- SMITH, R.A. and TURNER, M.J.B. (1974). Electronic aids for use in fatstock weighing. *Journal of Agricultural Engineering Research*, **19**, 299–311
- SOBEL, A.T., SCOTT, N.R. and HOFFMAN, G.W. (1980). 'Automatic milk yield data acquisition'. ASAE Paper, No. 80-5526. American Society of Agricultural Engineers, St Joseph, Michigan
- SPAHR, S.L., PUCKETT, H.B., FERNANDO, R.S. and RODDA, E.D. (1983). Analysis of in-line milk conductivity data. In *Proceedings, Symposium on Automation in Dairying*. pp. 79–88. Instituut voor Mechanisatie, Arbeid en Gebouwen, Wageningen
- STREET, M.J. (1979). A pulse-code modulation system for automatic animal identification. *Journal of Agricultural Engineering Research*, **24**, 249–258
- THOMPSON, P.D., RODRIAN, J.A. and DE VALL, F.B. (1982). 'Electronic activity monitoring as an aid to estrus detection'. ASAE Paper, No. 82-3028. American Society of Agricultural Engineers, St Joseph, Michigan
- TURNER, M.J.B., GURNEY, P., CROWTHER, J.S.W. and SHARP, J.R. (1984). An automatic weighing system for poultry. *Journal of Agricultural Engineering Research*, **29**, 17–24
- WORLEY, J.W. and ALLISON, J.M. (1984). 'Microprocessor control of poultry house environment'. ASAE Paper, No. 84-3025. American Society of Agricultural Engineers, St Joseph, Michigan

MICROPROCESSOR CONTROL OF THE ENVIRONMENT FOR FINISHING PIGS, USING LOWER CRITICAL TEMPERATURE

C.R. BOON and J.C. LOWE

National Institute of Agricultural Engineering, Silsoe, Beds, UK

Introduction

The lower critical temperature (LCT) has been studied for several years in relation to provision of the climatic environment for pigs; it is the lower limit of the thermoneutral zone, which in turn is the range of air temperatures for which the heat production of the pig is independent of air temperature. The upper limit of this zone is the upper critical temperature, and stock kept at temperatures in excess of this suffer thermal stress. The ideal climatic environment in which to house finishing pigs is one which is close to LCT but ensures that conditions do not fall below it as this would result in the wastage of food and poorer food conversion.

Research at the National Institute of Agricultural Engineering has emphasized the importance of the airflow pattern in relation to stock behaviour and performance (Randall, 1975), and it is now recognized that to create a good climatic environment at pig level with a forced ventilation system, it is of paramount importance to know how the air moves. By maintaining a constant known airflow pattern it is possible to ensure that the freshest possible air reaches all pigs in the building and, by directing the airflow correctly, that the lying and defaecating behaviour is controlled (Randall, Armsby and Sharp, 1983). From this research was designed and developed the high-speed jet ventilation system (Randall, 1977) which not only satisfies these two criteria but also overcomes many problems associated with wind interference at air inlets and outlets.

By using the fruits of this research it is possible to take advantage of more sophisticated methods of environmental control; initial experiments were made in a special building (Boon, 1978) to control the climatic environment of finishing pigs at their LCT (Boon, 1984). Rather than just sense and control the air temperature within the building, a microprocessor controller was designed to take into account the several environmental and husbandry factors which are needed to quantify LCT. These techniques were applied to a commercial 500-place finishing piggery (*Figure 19.1*). The piggery was fitted with a high-speed jet ventilation system which was modified to incorporate a microprocessor controller.

This chapter describes this system, which is one example of the way in which microprocessors can be of value to the pig producer.



Figure 19.1 Pen of pigs in a commercial 500-place finishing piggery with microprocessor control of the climatic environment to lower critical temperature

Lower critical temperature

A model for LCT was devised by Bruce and Clark (1979) by combining a model for the thermoneutral heat production of growing pigs and a model for the heat production of growing pigs below their critical temperature. These two models are based on the heat balance between the pig and its surroundings. For instance, included are the radiative and convective heat transfer, the sensible heat transfer to the air, and the minimum latent heat loss. The resultant model gives

$$\text{LCT} = T_b - \frac{Q_n(R_a + R_t) - Q_e R_a}{A\{1 + A_f/A[(R_a - R_f)/(R_t + R_f)] - A_c/A\}}$$

where T_b = deep body temperature ($^{\circ}\text{C}$), Q_n = thermoneutral heat production (W), Q_e = evaporative heat loss (W), R_a = thermal resistance of skin/air interface ($\text{K m}^2 \text{W}^{-1}$), R_t = thermal resistance of pig's tissue ($\text{K m}^2 \text{W}^{-1}$), R_f = effective thermal resistance of floor ($\text{K m}^2 \text{W}^{-1}$), A = surface area of pig (m^2), A_c = surface area of pig in contact with other pigs (m^2), and A_f = surface area of pig in contact with floor (m^2).

The important fact, from the point of view of the use of the LCT as a control algorithm for farmers and designers, is that the parameters in this equation can all be written in terms of five practical variables. These are: the live weight in kg (w);

the group size (n); the feeding level relative to maintenance level (x); the air speed at pig level in ms^{-1} (v); and the floor insulation factor in $\text{Km}^2 \text{W}^{-1}$ (r). The dependence of the parameters on these variables is as follows: Q_e , R_t , A and A_f are functions of w ; R_a is a function of w and v ; A_c is a function of w and n ; R_f is a function of w , n and r ; Q_n is a function of w and x ; and T_b is a constant (39°C). The individual equations for these parameters can be found in Bruce and Clark (1979).

The variables in practice

PRACTICAL CONSIDERATIONS

The use of LCT control on the farm depends to a certain extent on the type of husbandry involved. For finishing pigs in fully environmentally controlled fan-ventilated buildings there are two main systems—the ‘continuously stocked’ and the ‘all-in, all-out’. In the former the range of stock live weight is relatively constant, say from 30 kg up to 80 kg, whilst in the latter all the animals in the building at any one time are of approximately the same age and weight.

With continuously stocked systems, the required maximum and minimum ventilation rates are fixed and depend on the total stock in the building. The main proviso is that the ratio between the two extremes is 10:1, with the other stages in between determined from a simple heat balance, as described by Randall (1977). For all-in, all-out systems the ratio between maximum and minimum ventilation rates remains at 10:1, but the actual values increase as the stock grow so that, in fact, the ventilation system must be able to achieve a ratio of up to 30:1. Assuming the fans can be controlled with sufficient accuracy, this again points to the use of a microprocessor or computer for environmental control. A corollary of this is the necessity for the quality of the building to be high: all the ventilating air must enter

NIAE

Dependence of lower critical temperature on variables

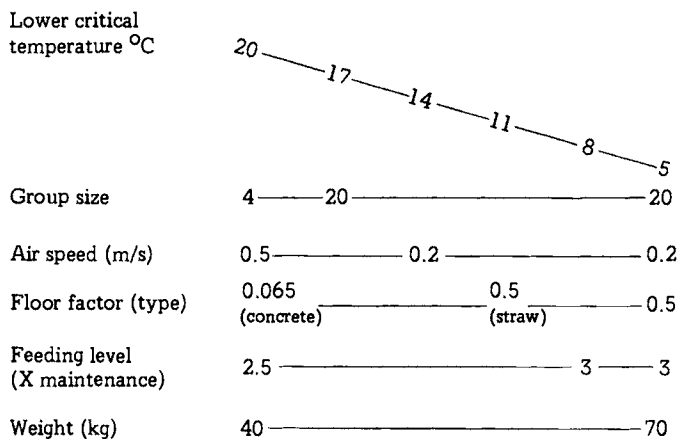


Figure 19.2 Example of the changes in the value of lower critical temperature with changes in the practical variables

the building through the designated inlets and not through cracks around doors or between structural panels. Also, the standard of insulation must be high.

The practical variables used can all change the value of LCT significantly and *Figure 19.2* gives examples of such changes. A more detailed discussion of the variables and how they were, or could be, used in the control system is given below.

LIVE WEIGHT

In an all-in, all-out system the live weight of the pigs would be updated automatically on a daily basis, and the value could be corrected when, or if, the pigs were weighed manually. Eventually, the problem of continuous monitoring of live weight may be solved but, until then, the growth curve has to be assumed. The experiments carried out on LCT control to date have involved continuously stocked management systems, in which the smaller pigs of 35 or 40 kg weight are more susceptible to departures from LCT than are larger pigs. This was shown visually by behavioural studies of pig huddling in relation to LCT (Boon, 1981). Thus, the value of live weight used for the control algorithm was that of the smallest pigs in the building. Under normal circumstances this remains virtually unchanged, the value used on the farm being 40 kg. Assigning a fixed value to live weight obviously simplifies the control to a certain extent, but provision was made for it to be changed manually if necessary.

GROUP SIZE

The average number of pigs in a pen depends upon the pen area, most pens being suitable for between 15 and 20 pigs. Over this range the change in LCT is not very significant, being about 0.5 K. It is of more significance if there are pens containing only one or two pigs, as is sometimes the case for sick animals. In this situation they could be as much as 4 or 5 K below their LCT, which is undesirable regardless of whether they are ill or not.

FEEDING LEVEL

The thermoneutral model of Bruce and Clark (1979) gives an equation for the energy required for maintenance, and the feeding level is defined in terms of this food energy in multiples of that required for maintenance. For pigs on a restricted diet the feeding level usually lies between 2.5 and 3 times the maintenance level, whilst on an *ad libitum* diet it may be 3 or more times maintenance level. The requirement is to know the energy value of the food, which varies with different mixings, and it may be more practical to use the energy value of the food as the variable. It would be most appropriate to use the energy value with an automatic feeding system in all-in, all-out husbandry, in which the quantities of food could be calculated and dispensed to the pigs' requirements as they grew.

AIR SPEED

The air speed at pig level is the most frequently changing variable, its value depending on the ventilation setting. The high-speed jet system is designed to

maintain an inlet air speed of 5 m s^{-1} at all settings, by varying the inlet size with the fan capacity being used. At the maximum ventilation rate, when all the fans are on, the quantity of air entering the building is large, for example for 500 pigs of about 65 kg live weight the ventilation rate required is about $17 \text{ m}^3 \text{ s}^{-1}$. The inlet gap is then the maximum, at say 0.22 m, and the air jet into the building has a large momentum. The consequent rotation of the air in the building produces an air speed at pig level of about 1 m s^{-1} , directed from the dunging area to the lying area. At the minimum ventilation rate, $1.7 \text{ m}^3 \text{ s}^{-1}$ in the example given, the inlet gap is only 0.025 m and, although the air speed is still 5 m s^{-1} , its momentum is low. At pig level the airflow is in the same direction as before but with a speed of $0.15\text{--}0.2 \text{ m s}^{-1}$, which is of the same magnitude as air speeds associated with the convection currents from the pigs. This difference in air speed from maximum to minimum is equivalent to about 6 or 7 K increase in LCT.

Ideally, the air speed should be monitored continuously, but there is no known suitable but inexpensive sensor which could be used. It is possible, however, to use the fact that each ventilation setting produces a unique mean air speed. If the system is calibrated by measuring air speeds at each ventilation setting, the measured values can be stored in RAM in the microprocessor memory. The reliability of the air speed value depends to a large extent on maintaining the ventilation system in good order. In particular, it is important to ensure that the sizes of the inlet gaps are correctly set and that all fans are operational.

FLOORING

The thermal characteristics of the floor are very important in the overall heat balance, because the animals lie down for considerable periods during which, assuming they are thermally comfortable, about 20% of their body surface is in contact with the floor. On a poorly insulated floor the heat lost by conduction can be significant. The values used for the thermal resistance of the floor have been measured by Bruce (1978) who gives values for various floor types. In the algorithm the value is scaled for the weight and posture of the pigs and also for the number of pigs lying together; the number is assumed to be the total number in the pen although, of course, this is not the case the whole time. Nevertheless, observations by Boon (1981) indicate that when the pigs feel cool they huddle together, in which case the algorithm is fully satisfied.

The two common extremes of flooring are solid concrete and straw. Placing straw as bedding on the concrete decreases LCT by about 4 K. All the values used assume that the floor where the pigs lie is not wet, and this should be the case if the high-speed jet system is working correctly in controlling defaecating behaviour.

Control using LCT

It has been explained *above* that the environmental conditions in a pen change when the ventilation system steps through its control stages, the important change being in the speed of the air over the pigs. For each stage there is a different value of LCT and thus a different 'set' point on the controller. This fact is one of the major differences between the standard and LCT controllers. The LCT controller attempts to minimize the difference between the air temperature and LCT but, in

so doing, the actual temperature in the building varies by several degrees. This is an important and novel concept to grasp since if the building temperature is considered in isolation from the other factors discussed above wrong conclusions are drawn.

Initial experiments on the use of LCT control with live pigs were carried out at the AFRC Institute of Animal Physiology at Babraham (near Cambridge, UK) (Boon, 1984) with 24 pigs housed in two pens in a specially designed building fitted with the high-speed jet ventilation system. The controller used in this instance was a Commodore microcomputer connected to a 100-channel data logging system, so that many measurements of the environmental conditions could be made.

Comparisons were made between control using LCT and conventional temperature control with a fixed set point of 18°C. The building housing the pigs was surrounded by a temperature-controlled shell which supplied the air to the piggery. This ambient air could be temperature cycled between 7 and 18°C over 24h periods to simulate typical diurnal changes in spring and autumn. The results showed that smaller pigs could be below their LCT for up to 30% of the time when conventional temperature control was used. The LCT control set point was (LCT + 2)°C, to take into account variations between pigs and the results obtained in experiments on group behaviour in relation to LCT (Boon, 1981), which indicated that at LCT there was still significant huddling of the group but at (LCT + 2)°C the incidence of huddling was low.

Figure 19.3 compares data from the two control modes for ambient temperatures, in 2-K bands, for pigs of 30–35 kg. It is clear that with LCT control the air temperature in the piggery was always 2K above LCT whereas, with a fixed set point of 18°C, the air temperature was often below LCT for considerable periods. Calculations based on the results of this experiment showed that savings of at least 20p per pig could be made using LCT control. These conclusions indicated that experimentation should be carried out on a larger scale.

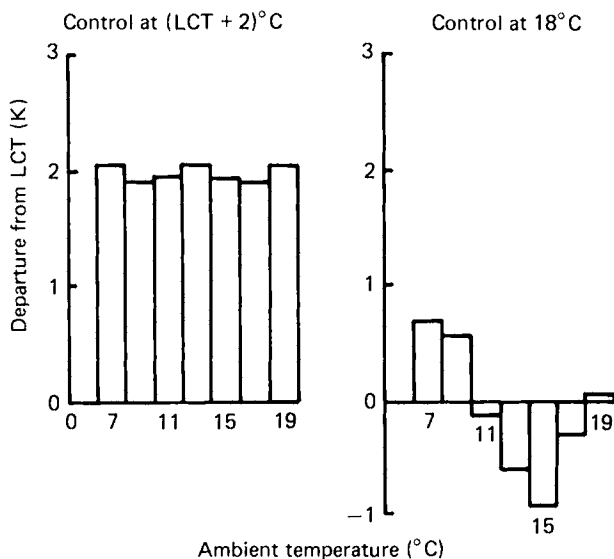


Figure 19.3 Departure of the air temperature from lower critical temperature in an experimental piggery for different ambient temperature bands. Left: control at (LCT + 2)°C. Right: control at 18°C

LCT control on the farm

A prototype LCT controller was installed in a 500-place finishing piggery which was equipped with a five-stage high-speed jet ventilation system. This system consisted of 17 fans controlled by a conventional electromechanical set point temperature controller. An adjacent identical building with a similar standard controller and throughput of pigs allowed direct comparison between the two control systems. Because the trials lasted only 6 months and because of the lack of replication inevitable in commercial operation, it was considered that no statistically significant comparisons of animal performance could be obtained and so no special arrangement was made to weigh pigs.

For reasons of cost and practicality it was decided that the LCT controller should drive the existing vent motor and fans. However, in view of the high overall system integrity required, it was decided that a single switch would be provided to transfer control back to the existing standard controller. Also, there would be automatic transfer of control in the event of a malfunction of the LCT controller. Because of the experimental nature of the installation it was necessary that the controller should also perform a data logging function, collecting temperatures and ventilation data from both piggeries and having the capacity to store one week's data.

One problem area was the control of the inlet vents. On the standard system a bank of microswitches in a slider system sets the vent position for each ventilation stage. In the LCT controller the vent position was achieved on a timed basis; to move from one stage to another the vent motor was switched on for a defined period of time. With this arrangement no feedback was required to signal the motor to switch off. Any small errors in position would obviously accumulate after several movements of the vent and so a daily calibration procedure was incorporated. Once per day, at feeding time, the vents closed to re-set their zero setting. This may be considered a potential hazard because if the power failed at the instant of closure problems would ensue, but the hazard was minimized by arranging the operation at feed time. Future designs will take this into account and provide a fail-safe action.

The ventilation stages were set such that a stage change caused the LCT, and thus the set point, to change by 1 K. In this piggery the minimum live weight was usually 40 kg, the pigs' lying area was solid concrete and they were fed at 3.0 times maintenance level. The average group size was 16. The measured air speeds at minimum and maximum ventilation rates were 0.15 and 0.9 m s⁻¹. From these figures it was estimated that seven ventilation stages were required compared with the five stages of the standard controller.

Many temperature control systems rely on a single sensor; indeed, the standard one monitored here was of this type. A single sensor often causes poor temperature control, however, because a single sensor may be above an empty pen; it is thus desirable to use more than one sensor. In the microprocessor controller, four sensors were used, installed around the building to give a mean value of temperature. If the reading of one sensor varied significantly from the other three its data were rejected and control continued using the remaining three.

With the required variables known, the controller computed the value of LCT and compared it with the actual temperature within the building. A control band was set at the set point ± 0.75 K so that if the building temperature fell outside this band the next stage, up or down, was called for. Normally, the controller averaged the temperature over a 10 min period before testing conditions but, after a stage

change had occurred, no further change was allowed for 20min to ensure that environmental conditions in the building had stabilized.

LCT controller hardware

A block diagram of the hardware is shown in *Figure 19.4*. The system can be divided conveniently into four sections: the transducers; the processor section; the power section; and the system changeover relays.

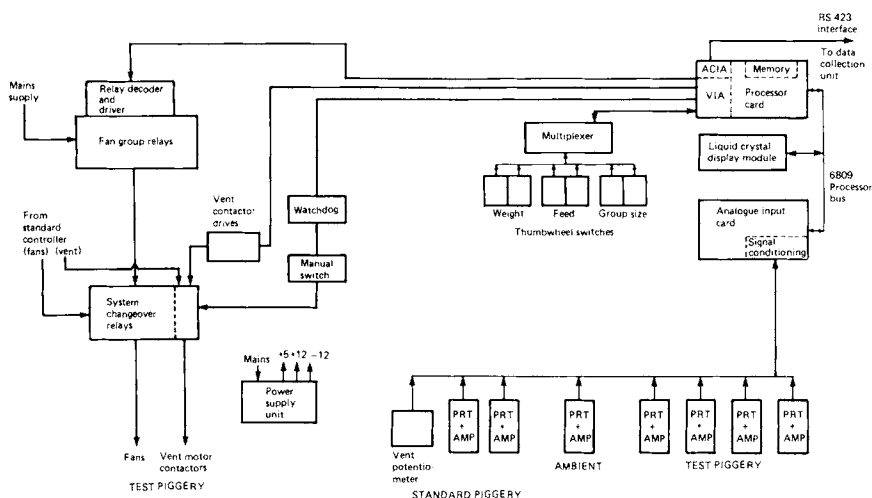


Figure 19.4 LCT controller—system hardware diagram

TRANSDUCERS

A total of seven platinum resistance thermometers (PRTs) were used: four measured the temperature of the air approaching the pigs in the LCT-controlled house (test piggery) and two measured the temperature in the standard piggery. The seventh was used to measure the ambient temperature and was placed in a Stevenson screen between the two buildings. These latter three PRTs were for data logging purposes only. The PRTs themselves protruded from small boxes containing epoxy-potted head amplifiers. These provided low-impedance signals of the order of several volts back to the controller, thus ensuring good immunity from electrical noise.

An eighth transducer, a linear potentiometer, was coupled mechanically to the wires which raised and lowered the inlet vent in the standard house. This provided data on the ventilation stage in that piggery for comparative purposes.

PROCESSOR SECTION

The processor card, analogue input card and user interface controls were housed in a glass-fronted cabinet which provided a reasonably moisture-proof environment

(to IP55). The processor card was a single card microcomputer from Control Universal Ltd, containing a 6809 central processor unit, three 8-kbyte EPROMs for program storage, one 8-kbyte CMOS RAM, with battery back-up, for the program working area and data storage, one 6551 ACIA for the serial link over which the data was transferred during collection (*see* section on data storage and collection), a 6522 versatile interface adaptor (VIA) which provided a pair of timers for vent timing and basic system timing, and two 8-bit input/output ports providing the interface with the remainder of the system.

The analogue input card, an in-house design, provided eight analogue channels for the transducers, each with gain and offset adjustment. The analogue-to-digital converter was an ADC 0816 8-bit, 16-channel data acquisition IC (of which only eight channels were used) and was interfaced directly to the 6809 bus.

Also interfaced directly to the 6809 bus was a two-line by 40-character liquid crystal display module which was mounted on the front panel of the cabinet. It displayed the temperatures at the four PRTs in the test house, the average of these four over the previous 10 min, the calculated LCT and the current ventilation stage of the test piggery (*Figure 19.5*). The front panel also had three pairs of thumbwheel switches, for the pig weight, group size and feed level, respectively. These switches interfaced via the VIA using a multiplexed system to reduce the number of input and output lines required.

A flexible multi-core cable, with plugs, connected the processor cabinet to the power cabinet to allow the removal of the processor cabinet for testing and development.

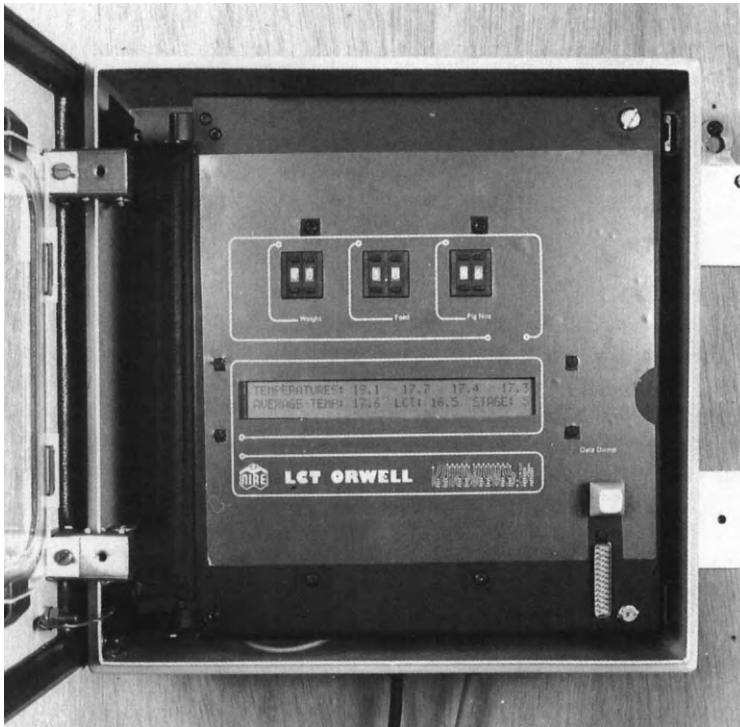


Figure 19.5 Panel of the LCT controller showing thumbwheel switches and display

POWER SECTION

This contained the regulated power supply units for the controller and also the fan control relays. There were six relays (ventilation stage 1 being two permanently operating fans) which were energized in sequence, bringing in the additional fans for each stage. *Table 19.1* shows the sequence of fans used and the ventilation throughputs of each stage. A 3-bit parallel code, representing the required ventilation stage, was supplied via the VIA to a decoder driver circuit, which energized the requisite relays. Also installed in this cabinet was the watchdog circuit. Every 5 s the processor card provided a pulse to the watchdog via a VIA line and any failure to do so caused the watchdog to 'time out' after a further 3 s. The power to the system changeover relays was cut and control of the piggery was returned to the standard controller.

Table 19.1 LCT CONTROLLER FAN SEQUENCE, VENTILATION THROUGHPUT AND INLET GAP FOR EACH STAGE

Stage	Number and size of fans (mm)	Throughput ($\text{m}^3 \text{s}^{-1}$)	Inlet gap (mm)
1	1 × 450	2.3	12.5
	1 × 400		
2	2 × 450	4.6	25.5
	2 × 400		
3	3 × 450	6.8	37.5
	3 × 400		
4	4 × 450	9.2	51
	4 × 400		
5	5 × 450	11.7	65
	6 × 400		
6	6 × 450	15.5	86
	8 × 400		
7	8 × 450	19.2	106
	9 × 400		

SYSTEM CHANGEOVER RELAYS

The supply to the fans from the fan control relays and the control lines from the processor card to the vent motor contactors were routed via a set of relays mounted in the cabinet of the standard controller. When these relays were de-energized, either by the operation of the system changeover switch or by a watchdog failure, the fan feed lines and the vent control line were routed back to the standard controller.

LCT controller software

Due to the relatively slow response times required in this application, together with the mathematical nature of some of the processing, a high-level language approach was adopted. The software was written in Motorola's 'BASIC-M' compiled BASIC language on a Motorola 'Exorset' development system. The source code was compiled into 6809 machine code and then 'blown' into EPROM, together with a

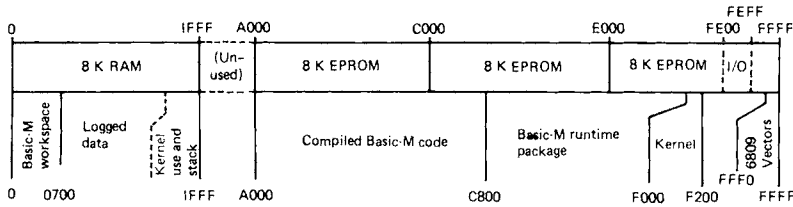


Figure 19.6 LCT controller—memory map

run-time module (supplied with the compiler) and a user-written 'kernel'. This latter, a set of assembly language routines, provided the interface between the BASIC-M run-time module and the controller hardware allowing, for example, the PRINT statement to write data directly to the liquid crystal display. A memory map of the controller is shown in *Figure 19.6*.

Data storage and collection

As outlined above, the LCT controller also acted as a data logger. Every 10 min the following five bytes of data were recorded: (1) the average temperature in the test piggery for the previous 10 min; (2) the average temperature in the standard piggery for the previous 10 min; (3) ambient temperature; (4) calculated LCT; and (5) ventilation settings of both buildings (condensed into one byte). These data were stored in a battery-backed CMOS RAM on the processor card. Each week a data collection unit was plugged into the controller and the data transferred over a standard RS-432 interface link. The data collection unit contained 6 kbytes of CMOS battery-backed RAM for the data storage and 2 kbytes of EPROM which held the assembly language communication program. The unit was operated from internal NiCad batteries for the short periods required for data transfer, the unit having an integral mains-operated battery charger. To allow for slight deviations from the normal weekly pattern of data collection, it was possible to hold 8 days' data in the controller. Subsequently, the data collected were transferred to a BBC microcomputer for initial analysis, but could also be transferred from this computer to a mainframe system for more detailed analysis.

Results and discussion

Experiments with the controller on the farm were started towards the end of July 1984, when the ambient temperatures were high, often 28°C or more. Only occasionally, at night, did the ambient temperature drop sufficiently to cause the controller to decrease the ventilation by one or two stages. Without cooling, the values of departure from LCT at the maximum ventilation rate follow the changes in ambient temperature (*Figure 19.7*). The lower curve shows the difference between the set temperature and the calculated LCT. Only on four occasions in the week does this difference disappear, indicating that during that particular week, ending 1 August 1984, the controller operated for only four periods. At these high ambient temperatures the adjacent standard house performed in a similar manner at the maximum ventilation rate.

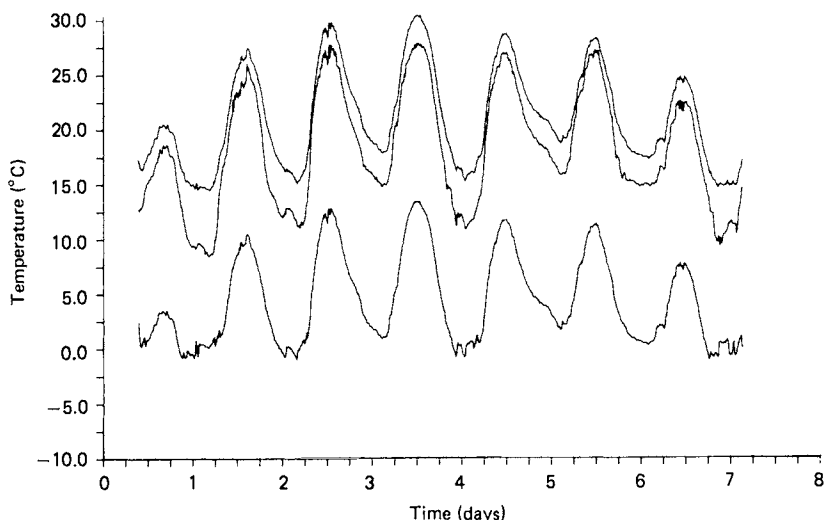


Figure 19.7 Temperature in test house and ambient temperature for week ending 1 August 1984. Upper: test piggery mean temperature. Middle: mean ambient temperature. Lower: departure from LCT

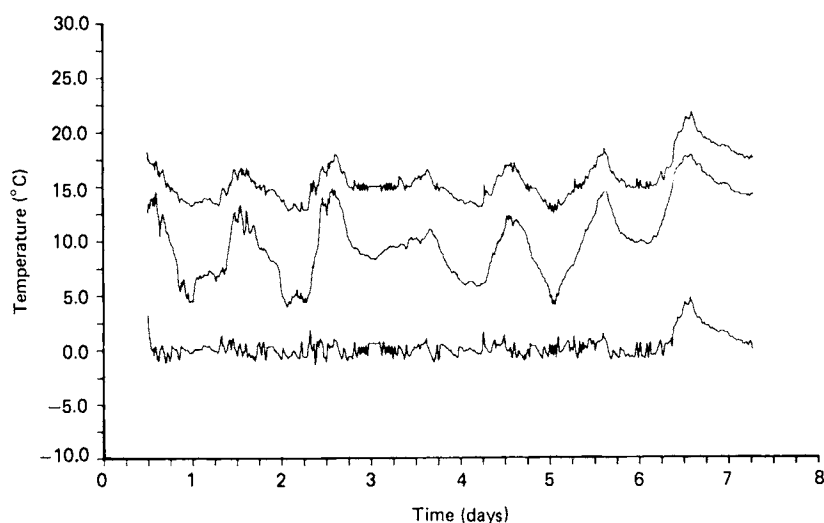


Figure 19.8 Temperature in test house and ambient temperature for week ending 9 October 1984. Upper: test piggery mean temperature. Middle: mean ambient temperature. Lower: departure from LCT

The high temperatures measured in the two piggeries highlight the advantage of the high-speed jet system over other types of ventilation. Although the temperatures were high, the high air speeds increased both the LCT and the upper critical temperature, keeping the stock well within their thermoneutral zone.

When the ambient temperature was between 5 and 15°C, the controller operated for most of the time. The lower curve in *Figure 19.8* shows that the temperature in the test house did not deviate significantly from the LCT; the uppermost curve

shows the important fact that the air temperature in the house varied by several degrees. During this period the controller was operating between stages 2 and 7 inclusive (see Table 19.1).

The actual controller setting was programmed to be the LCT although, as discussed earlier, $(LCT + 2)^{\circ}\text{C}$ was considered to be the optimal value. In this case the sensors were positioned 1 m above the division between the lying and dunging areas and were in the air stream flowing from the inlet to the side wall, whereas the pigs were in the air flow in the opposite direction. Measurements have shown that the air temperature at pig level would be approximately 1–2 K in excess of that at the sensor position. Thus the pigs, during the week shown in Figure 19.8, were always in their thermoneutral zone.

Data were recorded up to the end of 1984, covering a period of about 5 months, and showed that the controller performed as designed. The only omission, with the benefit of hindsight, was not being able to change the set departure from LCT manually. This was a feature which the stockmen would require, for instance, if there were disease in the building and a temperature increase or decrease were necessary.

Comparative data from the standard house during the 5 months were not sufficient in quantity for a statistical comparison of the two ventilation systems to be carried out. However, it was clear that the standard controller did not perform to specification, and that for much of the time it hunted through its stages from minimum to maximum, except when ambient temperatures were such that either the maximum or minimum rate was required. Whilst this action produced reasonably stable temperature conditions in the piggery, as shown in Figure 19.9, it was obviously not good for the system itself. Indeed, problems were experienced continually; e.g. the suspension wires for the vents broke on several occasions. The data for one week are shown in Figure 19.9, (the same week as for Figure 19.8); the lower curve shows a tendency towards more time below LCT than in the test house.

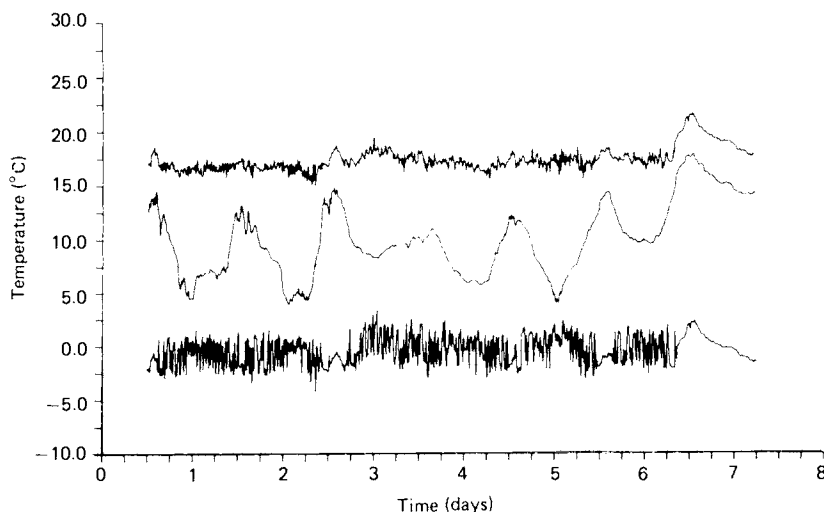


Figure 19.9 Temperature in standard house and ambient temperature for week ending 9 October 1984. Upper: standard piggery mean temperature. Middle: mean ambient temperature. Lower: departure from LCT

Conclusions

A commercial 500-place piggery was successfully controlled with a microprocessor controller which was designed using the concept of lower critical temperature (LCT). When the controller was acting, the departures from LCT were small, although the actual piggery temperature varied by several degrees as expected.

The experience and results gained from designing and installing a microprocessor controller in a commercial building have confirmed the feasibility of controlling the climatic environment using several variables. From both a welfare and an economic point of view, controlling for LCT should be an improvement, but careful design of both hardware and software is important.

The concept of controlling to LCT is acceptable only in modern, well-designed and well-maintained buildings.

References

- BOON, C.R. (1978). Airflow patterns and temperature distribution in an experimental piggery. *Journal of Agricultural Engineering Research*, **23**, 129–139
- BOON, C.R. (1981). The effect of departures from lower critical temperature on the group postural behaviour of pigs. *Animal Production*, **33**, 71–79
- POON, C.R. (1984). The control of climatic environment for finishing pigs using lower critical temperature. *Journal of Agricultural Engineering Research*, **29**, 295–303
- BRUCE, J.M. (1978). A suggestion for a ranked classification for floors of livestock buildings based on the conductive heat loss from recumbent animals. In *Proceedings, Symposium on Animal Housing—Injuries due to Floor Surfaces*. Cement and Concrete Association, Slough
- BRUCE, J.M. and CLARK, J.J. (1979). Models of heat production and critical temperature for growing pigs. *Animal Production*, **28**, 353–369
- RANDALL, J.M. (1975). The prediction of airflow patterns in livestock buildings. *Journal of Agricultural Engineering Research*, **20**, 199–215
- RANDALL, J.M. (1977). *A Handbook on the Design of a Ventilation System for Livestock Buildings using Step Control and Automatic Vents*. NIAE Report No. 28. National Institute of Agricultural Engineering, Silsoe
- RANDALL, J.M., ARMSBY, A.W. and SHARP, J.R. (1983). Cooling gradients across pens in a finishing piggery. II. Effects on excretory behaviour. *Journal of Agricultural Engineering Research*, **28**, 247–259

COMPUTER-AIDED CONTROL FOR A LIFE-CYCLE SWINE FARMSTEAD COMPLEX

J.A. DESHAZER, D.D. SCHULTE, J.E. PLESSING
and T.J. SIEBENMORGEN
University of Nebraska–Lincoln, USA

Fuel and electricity have been among the most rapidly rising farm production costs for the past decade. In spite of recent price falls, energy costs most certainly will rise again in the future. Researchers at the University of Nebraska (UN) have developed a research and demonstration farm at the UN Field Laboratory near Mead, Nebraska to study the practicality of using alternative energy sources and reducing future dependence on petroleum. The farm focuses on a life-cycle swine complex.

While the microprocessor has been used for environmental control of swine facilities and a solar heating system (Mitchell and Dury, 1980; Bundy, Dvorak and Mangold, 1982), the feasibility of computer-aided environmental control, as compared to the conventional controls used today, has not been investigated. Such information is needed by the producer to determine if a computer-aided environmental control system could be incorporated into his production facilities.

The objectives of the project were the development of computer control strategies to

1. integrate the efficient use of solar energy and hot water heat to maintain favourable environments in swine farrowing facilities;
2. control the production of electricity and hot water from a cogeneration unit which uses methane gas as the fuel;
3. determine load management methods for the farmstead.

Process controller

The swine farmstead complex utilized a General Electric programmable controller for data acquisition and control functions. An IBM personal computer was used to provide a more user friendly operator interface to the controller and was also used for herd management and record keeping.

The controller was an industrial unit commonly found in factories and assembly plants. The controller has the ability to handle analogue and digital inputs and outputs from many stations at a high scan rate, allowing fast and accurate monitoring and control, and was used to control a swine farrowing facility, methane digester, cogeneration system, and electric load management system and for general swine data acquisition.

The controller consisted of four components: (1) a central processor unit (CPU); (2) a program development terminal (PDT); (3) a data processor unit (DPU); and (4) several input/output units (I/O). Each of these components was housed in its own rack or module and was connected to the others via cable. The CPU, PDT, and DPU were all housed in the central computer room at the farm complex. The I/O racks were located near the areas being controlled.

The CPU is the 'brain' of the programmable controller. Scanning as many as 1024 inputs and outputs several times per second, the CPU performs all the decisions in the control process. The CPU receives input data, performs logical decisions based upon the stored program, and drives outputs as a result of these decisions. The input data received may be from switches, transducers, thermocouples, thumbwheels, or from other microprocessors. The outputs may drive relays, solenoid valves, or other solid state devices.

The PDT interfaces to the CPU and provides a visual display unit (VDU), a keyboard, and an internal tape drive to monitor the CPU's operation, input or edit programs, and save programs. The PDT also has ports for outputting programs to a printer or an external tape drive. The PDT has enough memory for program storage and permits off-line editing, so that programs may be edited without disturbing the CPU program. When the program is ready to be placed in the CPU memory, the PDT can be commanded to send the new program to the CPU while interrupting the CPU scanning for only 4m. The PDT also displays input, output, auxiliary input and output, and register tables for operating monitoring and control functions. The operator may override inputs or outputs in the off or on state or change register values for troubleshooting.

The DPU contains the processor, memory, and programs for receiving and storing data from the CPU or from external sources. The DPU contains 4096 16-bit data storage registers and up to 256K 16-bit words of file memory. Upon instruction from the CPU, the DPU can output this data in a user-specified format to an external printer, tape drive, or other computer via four serial communications ports at baud rates up to 9600 bps. This allows the controller to be used as a data acquisition tool, collecting, storing, and dumping the data on tapes.

The I/O units contain the necessary input or output boards for interfacing the CPU to various transducers or actuators. The boards provide optical isolation between the CPU and the transducers or actuators for protection from power spikes or equipment malfunctions. The I/O units can be placed near the controlled components for easier interfacing. The units communicate with the CPU via a parallel interface cable.

The controller uses a powerful industrial programming language called 'ladder diagram programming'. Ladder diagram programming consists of rungs of normally open or closed contacts, relays, and mnemonic functions to program the CPU's functions. The mnemonic functions consist of several mathematical and housekeeping commands that allow determination of error from set points and of status conditions, and data manipulation and transfer to the DPU.

OPERATOR INTERFACE

The IBM PC is used to provide 'user friendly' monitoring and control of the environmental conditions in the farrowing rooms. The PDT displays these data, but in a compact format without any identification of what the data represent. The IBM

PC communicates with the CPU via the DPU serial communication ports to display the data in an easy-to-read format.

The use of the IBM PC at the farmstead also provides an interface to the controller from other locations, via a modem. Monitoring and control of the environmental control system can be accomplished from the departmental computers in Lincoln, enabling quick checks on the system and saving time and money by reducing the need for trips to the farm. All programs for the IBM PC were written using BASIC and then compiled for faster operation.

Swine housing

Each farrowing room measures 5.5 m $\times$ 7.5 m. The principal source of heat for the rooms is solar energy. Ventilation air for the farrowing rooms is preheated by vertical solar collectors having solid concrete blocks as the thermal storage media. Inclined active solar collectors are used to provide hot air for underfloor heat storage, consisting of hollow core concrete block and sand. Additional floor heat in the farrowing rooms is provided by an in-floor warm water system, which can be heated by hot water from the cogeneration unit.

The rooms were adjacent to each other and placed between the gestation room and the mechanically ventilated nursery. Each room contained three conventional side-creep farrowing crates and three farrowing crates with enclosed front creeps. The enclosed front creeps measured 0.6 m deep by 1.5 m wide by 0.6 m high and were positioned directly in front of the sow stall. Two openings, 20 cm wide by 33 cm high, allowed access to the front creep from either side creep.

A favourable microenvironment for young pigs in the creep areas was provided by infra-red lamps and the in-floor heat storage system. One creep area of each conventional crate was heated with a 250 W lamp. The enclosed front creeps used 100 W and 25 W light bulbs. The 25 W bulb was used primarily as a continuous light source to attract the pigs to the creep. No heat was provided in the side creep areas.

The solar heated floor system consisted of 20 cm corrugated plastic pipes placed under the front creep and at the back of the conventional crates. Laterals of 10 cm corrugated plastic pipe were placed under each side creep of the conventional crates. No floor heat was provided to the side creep areas of the front creep crates. The pipes were set in a 50 cm deep layer of sand insulated by 5 cm of urethane foam on the sides and bottom. Urethane insulation of 5 cm thickness was also placed directly beneath the floor under the sow areas of all crates and the side creep areas of the front creep crates.

A hot water system provided backup to the solar floor heating system for periods when the collector was unable to maintain floor temperatures. The hot water system was a closed-loop arrangement made up of 2 cm diameter PVC pipe buried in the sand mass 18 cm below the floor surface. Hot water was supplied by a natural gas water heater or cogeneration unit at the farm. A pump distributes the hot water through the system. The flow of water to either room was controlled by solenoid valves placed directly below the distribution pump.

Ventilation was provided by propeller exhaust fans and a continuous slot air inlet along the top of the south wall. Baffles under the inlet slot directed air along the ceiling of the room and could be adjusted to maintain the desired static pressure. Three fans in each room (170, 300, and 870 $\ell\ s^{-1}$) were placed in the middle of the

north wall. A hood on the outside of the building protected the fans from wind interference.

The incoming ventilation air could be preheated by the solar Trombe south wall of the farrowing rooms. The Trombe walls were constructed of dry-stacked 20cm × 20cm × 40cm solid concrete blocks. An air gap of 0.5cm was maintained between blocks. The front face of the wall was painted with a matt black paint. Two glazings of Filon were placed in front of the wall and spaced 4cm apart and 4cm from the face of the wall. Air was pulled by the ventilation fans through an inlet slot at the top of the front glazing, down between the two glazings, through a slot at the bottom of the second glazing, and through the air gaps of the wall. The air entered the farrowing rooms through the continuous slot inlet at the top of the south wall of each room.

Incoming ventilation air could be directed through the wall for preheating or straight to the farrowing room inlet, selected by the position of a baffle at the top of the Trombe wall. When the baffle was closed the air was pulled through the wall, but if the baffle was open the incoming air bypassed the solar wall, thus reducing the heat load on the ventilation system during warm periods and conserving the stored heat for colder periods.

Environmental control

The computer-aided environmental control system was developed to perform the following functions:

1. to maintain the static pressure in the farrowing room at a desired level by adjustment of the inside baffle
2. to adjust the outside baffle to direct air to flow through or to bypass the solar wall to achieve the desired inlet air temperature
3. to control the operation of the ventilation fans to maintain the desired room temperature
4. to control the heat lamps and floor heat to provide a favourable microenvironment for the young pigs.

A diagram of the control system is shown in *Figure 20.1* and a flowchart of the programming logic is presented in *Figure 20.2*. The following sections describe in detail each of the system functions.

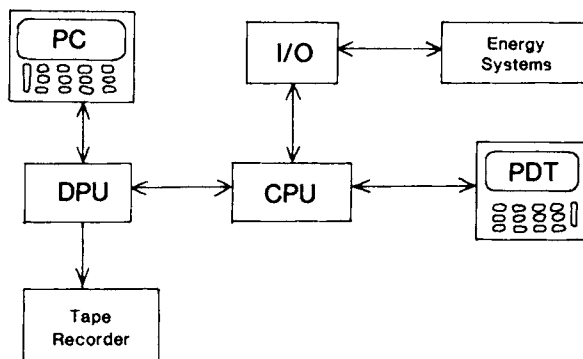


Figure 20.1 Computer-aided environmental control system

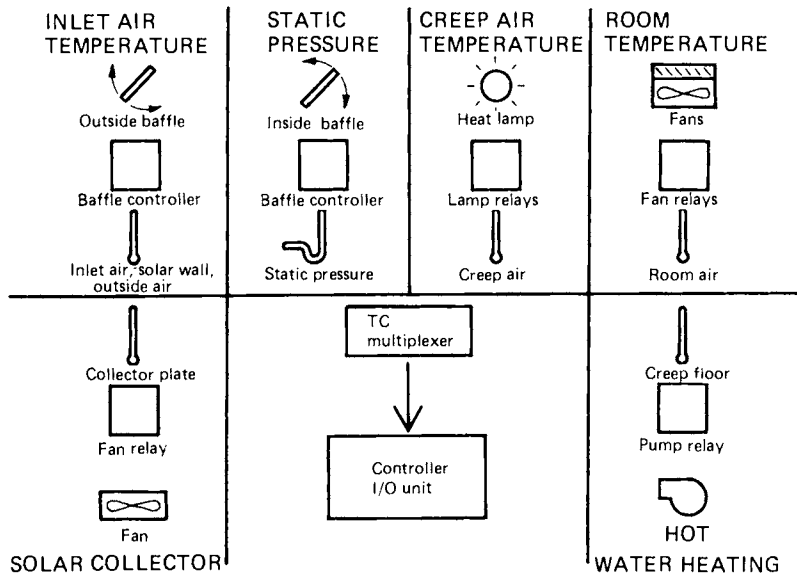


Figure 20.2 System functions and control

CONTROLLER INTERFACE

The computer-aided environmental control system used an I/O unit placed in the instrumentation room adjacent to the farrowing rooms to interface the inputs and outputs to the controller.

Type T thermocouples were used for all temperature measurements. An 8-channel analogue-to-digital board was used to condition the thermocouple inputs to be read by the controller, supplemented by a 240-to-8-channel multiplexer. The multiplexer is driven by the controller and scans a different group of eight thermocouples every 10s, repeating each temperature measurement every 5min. The thermocouples were placed inside PVC tubing when in places where sows or pigs could damage the wires. All thermocouple wires were run through a PVC wiring duct to the instrumentation room, where they were connected to the terminal panel of the multiplexer. The wiring duct protected the wires from the harsh environment and from damage during cleaning of the rooms.

Two Dwyer model 200 differential pressure transducers were used to provide a static pressure measurement. These transducers had a range of 0–12.5mm water column and provided an output of 4–20mA, directly proportional to the pressure difference. The output signal was converted to a 2–10V DC signal, for compatibility with an 8-channel analogue-to-digital card.

Digital inputs to the controller were handled by a 32-channel digital input board. Digital inputs included baffle position, fan operation, and mode and operation of the heat lamps and water pumps (computer on, off, or manual on). These inputs will be described in detail later. The controller was used to collect and record data for both rooms. The data collection routine was started at the beginning of each hour, when all current environmental control system registers, e.g. baffle positions, time lamps energized, etc. were transferred to the DPU together with temperature

readings. The data were dumped from the DPU to the magnetic tape drive at the end of the multiplexer cycle.

The controller drove the various system actuators through the use of a 32-channel digital output card. Most control functions were accomplished by relays driven by the individual channels of the output card. A 12V DC power supply provided power to the relay coils.

Pressure control

The controller converted the signal received from the pressure transducers via the analogue-to-digital board back to inches of water gauge and compared the value with that desired. If necessary, the inside baffle was adjusted by a baffle controller to maintain the desired static pressure. An event counter was used to estimate the position of the baffle for data acquisition and for the status display. Two lever switches were used to provide a signal to the controller when the baffle was completely open or closed. The controller used these signals to stop further operation of the baffle, preventing damage to the baffle or its controller.

Inlet air temperature control

The controller monitored the inlet air temperature via a three-point averaging thermopile placed in the air inlet slot into each room. Depending upon the sign and magnitude of the error of the inlet air temperature from its set point and the sign of the temperature difference between the solar wall average temperature and outside temperatures, the controller positioned the outside baffle via a baffle controller. An event counter and lever switches were used to estimate baffle position. *Table 20.1* summarizes the outside baffle operation according to the temperature differences.

Table 20.1 OUTSIDE BAFFLE POSITIONS

<i>Inlet air temperature minus set point temperature</i>	<i>Outside air temperature minus solar wall temperature</i>	<i>Baffle operation</i>	<i>Process</i>
Positive	Positive	Close*	Cooling
Positive	Negative	Open†	Cooling
Negative	Positive	Open	Heating
Negative	Negative	Close	Heating

*Close—outside air is directed through solar wall

†Open—outside air bypasses the solar wall

Room temperature control

The controller monitored the room temperature via thermocouples placed four feet (c. 120cm) above the floor surface in the middle of each room. The temperature was compared to set point temperature to determine the ventilation fan operation. *Table 20.2* shows the fan set points used.

Table 20.2 FAN OPERATION SET POINTS

Temperature deadband	3°C
Small fan low speed	7°C
Small fan high speed	24°C
Medium fan	26°C
Large fan	28°C

Creep air temperature control

The operation of the heat lamps in the creep areas could be controlled manually or by the controller. The controller monitored the temperature of the heated side creep area of each conventional crate and the front creep temperature of each front-creep crate. The averages of the three side creep temperatures and the three front creep temperatures of each room were determined separately. The control of each set of heat lamps was independent. The amount of time each group of heat lamps was on was recorded by the controller and the status of each group of heat lamps was displayed on the IBM PC.

The creep air temperature was set initially at 32°C at the beginning of each farrowing trial. The set point was then decreased by 3°C after each week until the end of the trial to provide the 'best' temperature for pig growth and health at the pigs' age.

Creep floor temperature control

The floor temperature of the creep areas was usually maintained by heat from the active solar collector system. The operation of the collector fan was determined according to the collector plate temperature. Floor temperature was not considered for collector fan operation since the fan needed to be operating whenever the plate temperature exceeded 32°C, to prevent damage to the collector.

If the active solar collector could not produce enough heat to keep the floor temperature above its set point, the controller activated the hot water backup system. The pump was started and the solenoid valve for that room was opened to allow water flow through the circulation lines. The floor temperature set point was equal to the creep air temperature.

Conventional control

For comparison, conventional environmental controls used thermostats and manual labour. Each ventilation fan was controlled by a thermostat, set at a particular temperature. The static pressure was monitored via a manometer in the room and was controlled by adjusting a baffle manually to vary the opening of the air inlet slot. Direction of the incoming ventilation air, through or bypassing the Trombe wall, was determined by positioning the outside baffle manually.

The infra-red heat lamps were switched on or off manually, as was the hot water backup system. The active solar collector fan was controlled by a thermostat which monitored the collector plate temperature.

Experimental procedure

Five trials were conducted to determine the feasibility of computer-aided control in a farrowing unit during the period of September 1983 to March 1984. The assessment of feasibility was based on reliability and accuracy of maintaining the target environment, based on energy savings and pig performance. Each trial coincided with the age of the young pigs, from farrowing to 4 weeks of age (*Table 20.3*). During each trial the environmental control of one room was accomplished using conventional control methods, while the other room used the computer-aided environmental control system. The method of control was exchanged between rooms after the completion of each trial to negate any effects of the building on the results. During each trial, various temperature measurements, energy consumption, and pig performance were recorded.

Table 20.3 TRIAL DATES AND ROOM ASSIGNMENT

<i>Trial</i>	<i>Trial period</i>	<i>Room using computer control</i>
1	22/09/83–19/10/83	West
2	02/11/83–28/11/83	East
3	07/12/83–04/01/84	West
4	11/01/84–08/02/84	East
5	15/02/84–14/03/84	West

Results

For each trial and control method, the data were reduced to 24h average values of the following variables:

1. Temperature (outside, solar wall, inlet, room, creep air, and creep floor)
2. Heat losses (building, ventilation, total)
3. Solar heat gains (Trombe wall, solar floor heating system)
4. Commercial energy inputs (electrical, natural gas).

The mean values of the above averages for each trial and control method are given in *Tables 20.4–20.7*.

It was found that the static pressure of one farrowing room affected the opposite room, due to openings in the flush tanks common to both farrowing rooms. Therefore, a comparison of the pressure control could not be made. It should be noted, however, that the computer-aided inlet baffle did respond to changes in the pressure in an attempt to achieve the pressure desired.

The computer control of the outside baffle resulted in a much more uniform inlet air temperature than for the conventionally controlled inlet air temperature. Manual operation of the outside baffle to achieve similar results would be difficult, since the baffle was operated during the late evening and early morning hours, not during times when labour would be available. The computer-aided control of the baffle reduced the Trombe wall heat gain for Trial 1, therefore reducing the heat load on the farrowing room. The values of Trombe wall efficiency in excess of 100% in *Table 20.6* may be ascribed to the reflection of solar radiation from snow cover. The end result of the computer-aided control was a 52% reduction in the ventilation energy requirement. The computer-aided control system consistently

Table 20.4 SUMMARY OF THE ENVIRONMENTAL TEMPERATURES MEASURED DURING FIVE TRIALS. ALL VALUES ARE A MEAN OF THE 28-DAY TRIAL PERIOD

Trial	Treatment	Temperature (°C)					
		Outside air	Solar wall	Inlet air	Room air	Creep air*	Creep floor*
1	WC	17.0	24.9	20.4	23.3	28.5	30.6
	EM		20.8	21.3	23.4	33.6	32.2
2	EC	4.7	14.5	14.8	20.4	27.4	32.5
	WM		11.8	11.7	18.5	27.3	27.1
3	WC	-8.5	2.9	7.0	16.1	25.9	30.7
	EM		7.5	10.3	16.9	25.6	34.4
4	EC	-3.2	9.8	10.7	19.0	25.2	33.1
	WM		10.0	10.4	16.0	26.8	28.0
5	WC	1.9	11.7	10.5	16.4	25.6	26.7
	EM		15.3	15.1	19.5	27.8	32.0

*Creep temperatures are the mean of the side and front creep areas

W (west room), C (computer control), E (east room), M (conventional control)

Table 20.5 TOTAL FARROWING ROOM VENTILATION, BUILDING AND TOTAL HEAT LOSSES FOR EACH 28-DAY TREATMENT

Trial	Treatment	Heat loss (MJ)			Per cent V/T*
		Building	Ventilation	Total	
1	WC	469	1523	1992	76
	EM	452	916	1368	67
2	EC	1120	2940	4060	72
	WM	980	5796	6776	86
3	WC	1706	5010	6716	75
	EM	1826	3976	5703	70
4	EC	1501	4256	5757	74
	WM	1323	2962	4285	69
5	WC	1385	3244	4629	70
	EM	1263	2353	3616	65

*Percentage of total heat loss due to ventilation

Key as Table 20.4

Table 20.6 SOLAR HEATING INPUTS TO THE FARROWING ROOMS FOR EACH 28-DAY TREATMENT

Trial	Treatment	Energy inputs (MJ)		Available solar radiation* (MJ)	Trombe wall efficiency (%)
		Active collector	Trombe wall		
1	WC	-40	1940	5270	37
	EM	317	2398		46
2	EC	-183	5323	3596	148
	WM	-100	5399		150
3	WC	-9	8389	5194	162
	EM	-6	9906		191
4	EC	-11	7127	6288	113
	WM	19	6955		111
5	WC	-71	4855	5025	97
	EM	11	6815		136

*Radiation on a vertical surface calculated from horizontal measurements.

Key as Table 20.4

Table 20.7 TOTAL COMMERCIAL ENERGY INPUTS (MJ) TO THE FARROWING ROOMS FOR EACH 28-DAY TREATMENT

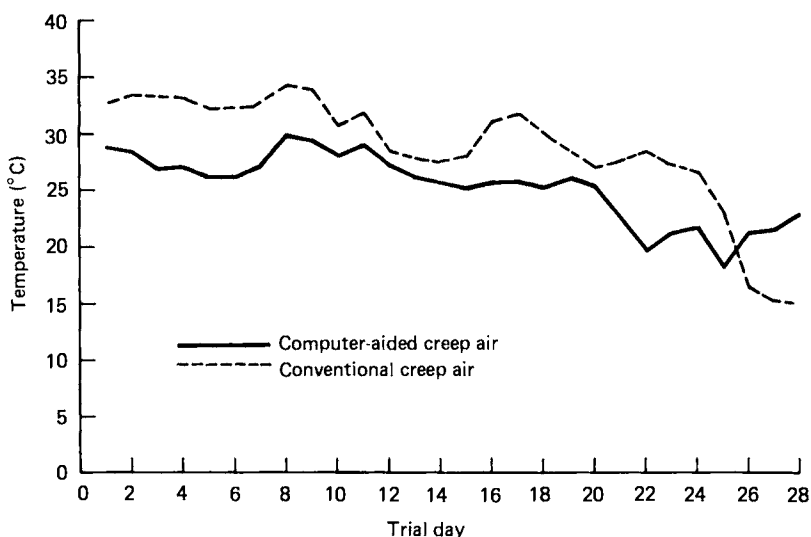
Trial	Treatment	Electrical			Natural gas*	Total input
		Ventilation fans	Collector fans	Heat lamps		
1	WC	163	170	1668	7370	9389
	EM	338	104	2548	0	3000
2	EC	159	48	1960	1848	4116
	WM	196	28	2548	0	2772
3	WC	181	64	2493	9038	11776
	EM	193	40	2548	9268	12048
4	EC	175	96	2264	2519	5054
	WM	184	56	2461	9034	11735
5	WC	81	76	2548**	9408**	12113
	EM	194	63	2548**	9408**	12213

* Assuming 70% efficiency of the water heater.

** Due to programming error, time of operation values were not available. Equipment was assumed to be operating continuously.

Key as Table 20.4.

used less energy for ventilation for the remaining trials also. This was due to a more uniform room temperature monitored by the computer-aided system. *Figure 20.3* presents typical average daily creep air temperatures achieved by both control methods. The computer-aided heat lamps maintained a more uniform creep air temperature on an hourly basis than did the conventionally controlled lamps. The conventionally controlled lamps were usually left on continuously throughout the trials, which resulted in the higher average temperatures, but also resulted in a higher electrical energy consumption (1700 MJ). A major problem with the computer-aided control of the lamps was damage to the thermocouples used to measure the creep air temperatures in each heated creep area. Damage to

**Figure 20.3** Typical computer-aided controlled creep air temperatures and conventional creep air temperatures

thermocouples produced bad temperature measurements, which caused a switch to the 'fail-safe' mode. Additional protection of the thermocouple wires in the creep areas solved this problem.

Control comparisons for the creep floor temperature produced mixed results (see *Table 20.7*). Over all five trials, the computer-aided system used 2475 MJ more energy from natural gas than the conventional control system, with most of the difference due to Trials 1 and 2. The conventional system did not use the hot water system during Trials 1 and 2, but did during Trials 3, 4 and 5. In these last three trials the computer-aided system saved 6745 MJ of energy. One result was consistent for both control methods: more energy from the hot water system was used to heat the air than the floor. This is indicated by 'negative' heat gains by the active collector, as shown in *Table 20.6*. The comparison of the temperature of the air from the collector plate and the sand mass temperature should also be used to determine collector fan operation.

The amount of electrical energy used for ventilation and heating lamps by the computer-aided system was 2070 MJ less than by the conventional method, which amounts to 69 MJ per litter or US \$1.31 per litter (1.9 cents per MJ). For the five trials this amounts to US \$6.50 per farrowing crate during the heating season. The amount of electrical energy saved by the computer-aided system was greater for Trial 1, which was during September, than for the other trials. It appears that the computer-aided control system is better adapted to the spring and fall (autumn) seasons, when the outside temperature fluctuates widely between day and night. During the summer months there would probably be negligible energy savings, due to the similarity of operation of the two control methods.

There was no significant difference in number of pigs farrowed, average daily gain, or the average weaning weight of the pigs between the computer-aided or conventional control systems. Therefore, any additional costs of the computer-aided system must be repaid in energy savings.

Conclusions

The overall conclusion of this research was that computer-aided environmental control is feasible for a farrowing facility. Specific conclusions were that:

1. A computer-aided control system could be used to control the environmental conditions of a farrowing facility.
2. Both the computer-aided and the conventional environmental control methods were able to maintain adequate environmental conditions of the farrowing rooms, although not always within the desired operating ranges. The computer-aided control provided more uniform temperatures than the conventional system.
3. The computer-aided control system saved 2070 MJ of electrical energy per litter farrowed, a saving of US \$1.31.
4. Pig performance did not differ between control methods.

Cogeneration and digester system integration

FARMSTEAD ENERGY DEMAND

In sizing the cogenerator for this farm the electrical and thermal demands of components that could be served by the cogeneration system were first estimated.

Table 20.8 MAJOR ANTICIPATED ELECTRICAL LOADS

Device	No.	Load size*		Seasonal operation				Operating time Duration/time interval
		kW	HP					
				S	F	W	S	
Grain and feed handling centre								
Elevator leg	1	3.73	5.0	×	×	×	×	Intermittent, 3 h/day at harvest
Grinder-mixer	1	3.73	5.0	×	×	×	×	1 h/2 days
Steel dump hopper	1	1.49	2.0	×	×	×	×	Intermittent, 3 h/day at harvest
Drag conveyor	1	1.12	1.5	×	×	×	×	Intermittent
Nutri-blender	1	0.75	1.0	×	×	×	×	1 h/2 days
Grain bins								
Drying fan	2	3.73	5.0		×	×†	×†	Continuous
Screw auger	2	2.24	3.0	×	×	×	×	Intermittent
Spreader	2	0.37	0.5		×	×	×	Intermittent, 3 h/day at harvest
Screw auger	1	1.49	2.0	×	×	×	×	Intermittent
Drying fan	1	0.56	0.75		×	×	×	See footnote†
Spreader	1	0.37	0.5		×			Intermittent, 3 h/day at harvest
Inclined auger	1	1.12	1.5	×	×	×	×	Intermittent
Feed bins								
Inclined auger	5	0.37	0.5	×	×	×	×	Intermittent
Feed transfer								
Pneumatic pump	1	2.24	3.0	×	×	×	×	2.0 h/2 days
Feed auger	1	0.37	0.5	×	×	×	×	2.0 h/2 days
Cogeneration system								
Cogen. water pump*	1	0.06	0.08	×	×	×	×	5 h/day
Furnace water pump*	1	0.06	0.08		×	×	×	Intermittent
Furnace fan*	1	0.25	0.33		×	×	×	Intermittent
Digester								
Gas recirculation pump	1	0.75	1.0	×	×	×	×	5 min/hour
Compressor	1	0.75	1.0	×	×	×	×	30 min/h†
Digester water pump*	1	0.37	0.5	×	×	×	×	1 h/day

Alcohol fuel plant

Lightnin mixer	1	1.12	1.5		×				4 h/day
Fermenter pump	6	0.37	0.5		×				2 pumps continuous
Cook-transfer pump	3	0.37	0.5		×				10 h/day
Distillation pumps	3	0.37	0.5		×				10 h/day
Ceiling fan	1	0.37	0.5		×				Continuous
Air compressor	1	0.37	0.5		×				Intermittent
Makeup water pump	1	0.19	0.25		×				Intermittent
Boiler fan	1	0.25	0.33		×				6.5 h/day

Swine buildings

Scraper	1	1.12	1.5	×	×	×	×		20 min/day
Solar fan*	3	0.07	0.1	×	×	×	×		7 h/day
Vent. fan (winter)*	3	0.03	0.03		×	×	×		Continuous
Vent. fan (spr/fall)*, **	3	0.25	0.33	×	×		×		Continuous
Vent. fan (summer)*, ††	3	0.37	0.50				×		Continuous
Heat lamp*		2.25	—	×	×	×	×		Continuous
Lights – day*		2.42		×	×	×	×		Continuous
Lights – night*		1.5		×	×	×	×		Continuous

*All loads are 208V, 3 phase unless footnoted by * which indicates 120 V, single phase

‡Represents average figure over the course of a day

**Two of the three spr/fall fans have 0.03 kW (1/29 HP) motors

††Two of the three summer fans have 0.19 kW (¼ HP) motors

†Operated approximately 4 h/week when conditions are correct for aeration

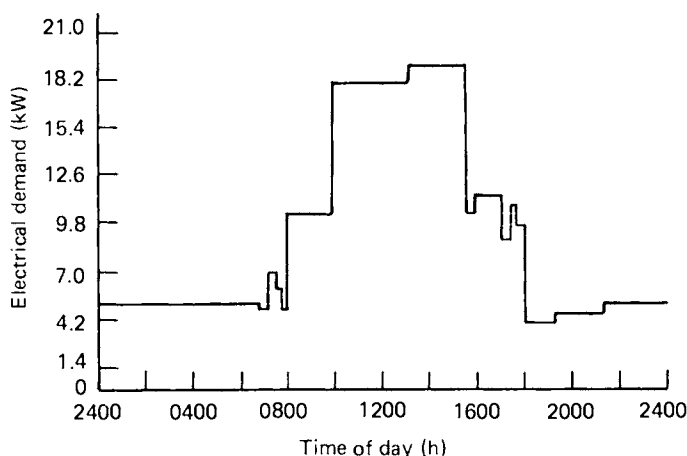


Figure 20.4 Anticipated electrical demand profile for summer

Table 20.8 displays the major electrical loads and their expected operating times. Schedules of the farm electrical loads were estimated and daily demand curves were drawn. Examples of these estimated demand curves for summer and autumn operations are shown in *Figures 20.4 and 20.5*.

The grain and feed handling centre demands the largest set of electrical loads on the farm throughout the year, as shown in Table 20.8. Feed preparation, feed and grain transport, and natural air grain drying account for the primary loads of this centre. The electrical peaks in *Figures 20.4 and 20.5*, of 20–22 kW, can be managed to utilize the full benefit of cogenerated electricity. Although not utilized in this study, the grain and feed handling operations offer a target for such management as many of these loads can be scheduled in *lieu* of other farm electrical loads.

Several thermal loads exist on the farm which could be supplied or supplemented by cogenerated hot water. The primary use for cogenerated hot water was to supply

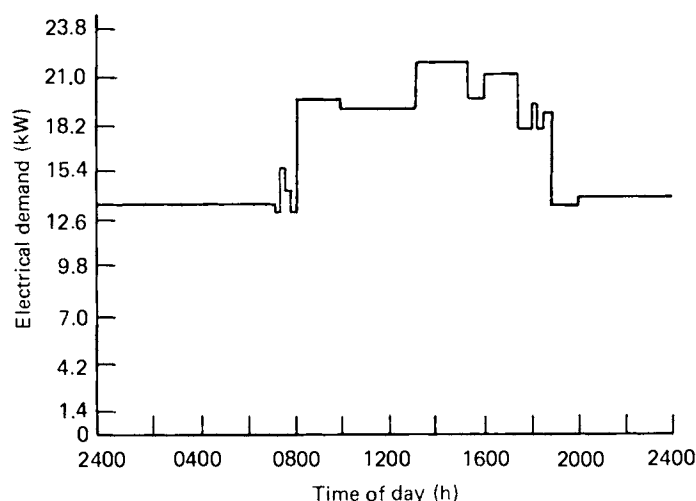


Figure 20.5 Anticipated electrical demand profile for autumn

the thermal demands of the digester. The heating demand of the digester during January was calculated to be 215 MJ day^{-1} . This heating demand consists of influent manure heating and digester vessel heat losses. The farm centre comprises a 97.5 m^2 office and laboratory area located within a steel-framed building. The heating load of this area for an outside air temperature of -18°C was calculated to be 12.7 MJ h^{-1} . This load was assigned second priority for use of cogenerated hot water. A third use for hot water exists in the in-floor, water heating system of the farrowing building. This building is primarily heated by passive and active solar air systems. A natural gas hot water heater rated at 58.0 MJ h^{-1} input provides backup and supplemental heating to the farrowing house through the in-floor heating system. Cogenerated hot water could provide a portion or all of this energy.

BIOGAS COLLECTION AND STORAGE

A fundamental determinant in integrating a biogas-fuelled cogeneration system into a farmstead is the relationship of biogas availability to the previously defined energy demands. Due to the layout of the swine buildings, it was practical to collect manure for biogas production from only the growing/finishing building. An estimated $1.0 \text{ m}^3 \text{ day}^{-1}$ of manure with 9% total solids content is scraped mechanically from below the slats of the growing/finishing unit. Under design conditions, this manure is loaded once per day into a 22 m^3 liquid volume, partially buried anaerobic digester. The design biogas production rate is $38 \text{ m}^3 \text{ day}^{-1}$ which corresponds to a gross energy production rate of 855 MJ day^{-1} , assuming an energy density of 22.4 MJ m^{-3} .

A 1.14 mm hypalon cover placed over the digester slurry surface serves to capture the evolved biogas which is then passed through a Nelson filter and an iron sponge filter to remove mercaptans, hydrogen sulphide and water vapour. The biogas is then compressed to a maximum pressure of 1725 kPa and stored in a 3.8 m^3 LP gas tank using a 0.746 kW (1hp) LeRoi Dresser compressor.

The LP gas tank is capable of storing approximately 36h of anticipated biogas production. Pressurized storage for this period was selected to provide flexibility in managing the cogenerator within farmstead energy demands. In particular, having the capability to store the biogas over this time span allows operation of the cogenerator during peak electrical demand periods. As discussed later, the timing of electricity production is critical under most utility buy-sell arrangements. Another advantage of the biogas storage is that engine maintenance and short down-times are possible without wasting biogas. Also, the engine operates at higher shaft efficiencies when under full load, which is possible only if sufficient biogas is available. However, the use of a compressor/high-pressure storage tank arrangement increases the initial cost, electrical power requirements and complexity of the biogas system compared to low-pressure 'bag' storage systems.

THERMAL ENERGY MANAGEMENT

Selection of the cogenerator size in this and many other cases is influenced primarily by the electrical demands of the farmstead and to some extent by the size of commercially available units. However, effective utilization of the cogenerated thermal energy represents a significant integration problem. Prior to discussing the

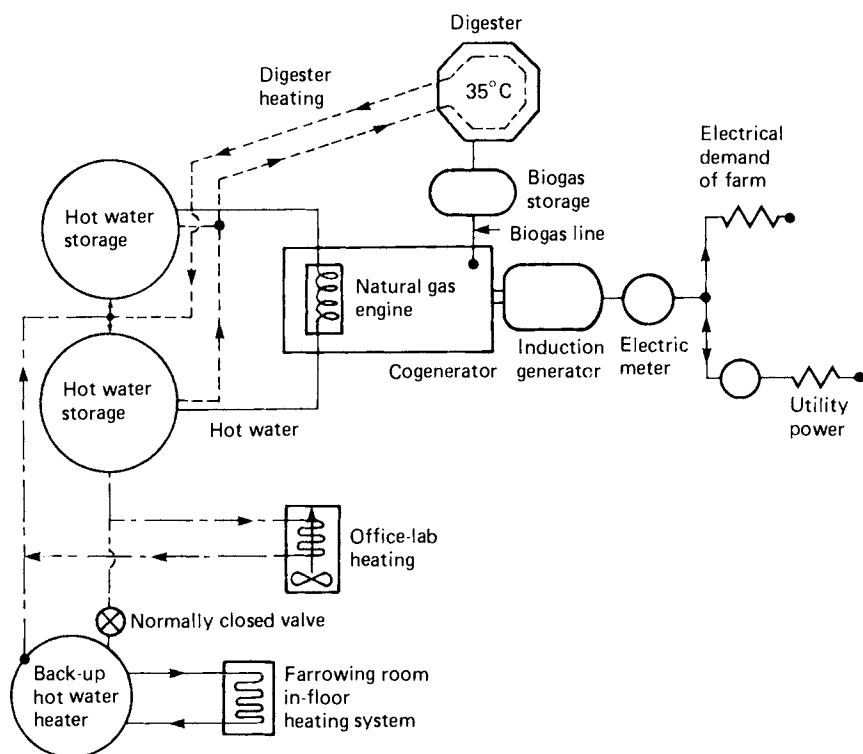


Figure 20.6 Diagram of the cogeneration system

method of integrating cogenerated thermal energy into this farmstead, the reader is referred to *Figure 20.6* for a scheme of the system.

The digester and biogas storage tank are located approximately 20m from the steel-framed building housing the cogenerator and hot water storage tanks. Biogas flows through a 2.54cm pipe from the gas storage tank to the engine. Two in-line pressure regulators reduce the pressure to 2.0kPa at the engine. Hot water used to heat the digester slurry is pumped through insulated, 3.8cm black iron pipes from the storage tanks to the digester. This piping continues into the manure slurry to serve as the heat exchanger in the digester. The hot water pipes and the biogas line were placed in a 20cm PVC conduit and buried underground. Instrumentation cable for monitoring and controlling the digester was also placed inside this conduit. The PVC conduit protects the pipe insulation and the instrumentation cable, as well as preventing some heat loss from the hot water pipes.

Thermal energy is collected from the engine coolant system. The engine water pump circulates coolant through the water jacket and then through an exhaust heat recovery heat exchanger. After exiting this heat exchanger, a thermostatic mixing valve causes a proportional amount of the coolant to pass through a tube-in-shell heat exchanger and an auxiliary radiator, returning to one of the two inlet ports of the mixing valve. The thermostatic valve mixes this cooled portion with the remaining portion of the coolant flow, to maintain a constant engine inlet coolant temperature of 87.8°C. The tube-in-shell heat exchanger supplies heat to the hot water storage system. Thus, the coolant water for the engine and the hot water

storage system form two separate loops. If the engine coolant water is not sufficiently cooled in the tube-in-shell heat exchanger, the fan of the auxiliary radiator is automatically turned on to remove excess heat.

As mentioned previously, the top priority assigned for use of the cogenerated thermal energy was to provide heat to the digester. In order to allow some cogenerator down-time without using the backup hot water supply, and to provide flexibility in scheduling cogenerator operation during times of peak electrical demand, the hot water storage was sized to maintain the desired digester slurry temperature and to heat the influent manure to 35°C for a one-day period of digester operation during January. This criterion included the assumption that 1.0 m³ of influent manure would be heated from 2°C to 35°C. Thus, 142 MJ was needed for this portion of the daily digester heating requirement. The associated conductive heat loss for the digester was calculated to be 73 MJ day⁻¹. A storage capacity of 2.27 m³ was selected since a 28°C storage temperature differential would supply the digester heating requirement for an entire day. The heat recovery rate from the tube-in-shell heat exchanger of the cogenerator was estimated to be 88 MJ h⁻¹ when the engine operated at 13 kW output load. This corresponds to 45% of the biogas energy input to the cogenerator. Alternatively, the 2.27 m³ water storage is expected to be heated to approximately 39°C when an entire day's biogas production is utilized by the cogenerator.

Two 1.14 m³ steel tanks were chosen for hot water storage in order to achieve a greater water temperature stratification than could be possible in a single tank. The plumbing was constructed so that water to be used for heating purposes is drawn from the tops of the tanks, while for collecting heat from the cogenerator it is drawn from the bottom of the 'cooler' tank and pumped to the top of the 'hotter' tank. This improves heat collection and hot water use efficiencies. Each tank is insulated with 5 cm of fiberglass insulation.

Hot water in excess of the digester heating demand is used to heat the office and laboratory areas, located 12 m from the cogenerator. Water is piped to a water-to-air heat exchanger incorporated in the air duct system of the building.

Hot water from the storage in excess of the above demands is used if needed to supplement the solar floor heating system in the farrowing house. As shown in *Figure 20.6*, water pipes are connected to the natural gas-fired hot water heater, mentioned previously, which serves as a backup heating system for the solar in-floor heating system. In the event of cogenerator malfunction or inability to meet the entire hot water demand, backup hot water for the digester and office heating demand is supplied by the natural gas heater. Plumbing allowed heating of only one of the storage tanks during backup for speed of response.

COMPUTER-AIDED CONTROL

The process controller described earlier also controls operation of the pumps, motors, and cogenerator in the biogas production and utilization system. Thermocouples in the digester sense temperature and call for hot water via the process controller. A second set of thermocouples in the hot water storage system monitors the temperature and hence heat energy available. Depending upon the amount of hot water in storage, the controller may instruct the cogenerator to start using biogas to supplement the hot water supply. Pressure transducers in the digester provide signals to initiate the automatic removal of biogas from the

digester to the storage tank. A pressure transducer and a thermocouple in the storage tank provide information to the CPU which corrects gas storage to standard conditions for data storage in the DPU. The I/O units relay information to the digester and cogenerator for control of valves, engine start and stop, the compressor motor and gas mixer. Status of these items as well as pressures, gas in storage and temperatures are displayed on the PDT in the farm's computer room.

CONTROL STRATEGIES

The availability of a device such as a process controller enables the use of differing operating strategies. The following three strategies were investigated using a simulation model of the energy-integrated farm (Siebenmorgen, 1984).

Starting strategies

Electrical demand, hot water demand, and biogas availability were identified as the critical variables in formulating cogenerator starting strategies. Three alternative starting strategies were formulated in which these three variables served as the respective primary criteria. A constraint imposed on all strategies was that before the cogenerator could be started, enough biogas had to be available in the storage tank to fuel the engine for 4 h. Further, upon starting, the engine remained on until the biogas in the storage was depleted. The formulated strategies were as follows.

1. To start the cogenerator when the farm electrical demand exceeded 13 kW. This insured that, at least initially, all of the cogenerator electrical output would be used on-farm. Electrical demand data indicated that this level was exceeded when the feed mill was operated.
2. To start the cogenerator when the average temperature of the hot water storage declined to 43°C. This was considered to be the minimum temperature at which water could be used efficiently to heat the digester slurry.
3. To start the cogenerator when the biogas storage was full, i.e. level in storage exceeded 68 m³. This was an 'overriding' strategy, in that the cogenerator would always start when the storage was full so that no biogas would be vented to waste through the pressure relief valve of the high-pressure storage tank.

The cogeneration system operation was simulated for each of the three strategies for one-week periods in three typical seasons—summer (15 to 23 July), fall (15 to 23 October), and winter (15 to 23 January). The periods represented the range of expected demand. The electrical demand of the farm in these time periods was lowest in the winter and highest in the fall, when two 3.73 kW grain-drying fans were operated.

Sensitivity analysis

A sensitivity analysis was performed to determine the effect on system performance of the alternative operating protocols. For electrical demand additional set points for cogenerator starting were chosen of 7 and 10 kW. The cogenerator operating times were 3, 4 and 5 h. These times were applied to each of the starting strategies,

creating a 3×5 , 'minimum operating time by starting strategy' matrix. The sensitivity analysis was performed only for the winter period, since both the electrical and thermal demands were critical during this season. The hot water demand set point was not varied, since the thermal storage set point of 43°C was considered the minimum to satisfy thermal demands, while raising this set point would only increase the number of cogenerator cycles.

The results of the model were compared using criteria which indicated the frequency of cogenerator starting and the degree to which digester and space heating demands were met. An economic approach was formulated to evaluate the results. This approach involved representing the performance of a strategy by the percentage of cogenerated electricity sold to the utility (F_E) and the percentage of cogenerated thermal energy dissipated (to waste) by the cogenerator radiator (F_Q). The economic results were presented to allow comparison with values of F_E , F_Q , and electricity and fossil fuel rates other than those values used for illustration.

The results of this study indicated that:

1. A large percentage of cogenerated thermal energy was dissipated by the cogenerator auxiliary radiator during summer and fall conditions. F_Q reached 0.63 for one summer simulation trial.
2. Throughout the year, most of the cogenerated electricity was used on-farm, although winter values of F_E reached 0.43.
3. The annual average values of F_E and F_Q were found to be 0.22 and 0.37, respectively.
4. Neither starting strategy nor minimum operating time affected significantly the monetary value of cogenerated energy for the price structure and energy demands of the farm investigated. The greatest monetary difference of the simulations of this analysis was 12% of the attainable value.
5. A favourable strategy for year-round use is to start the cogenerator when the electrical demand exceeds 13kW. Although not included in the electrical rate structure of most small farms, demand charges would be reduced or eliminated using this strategy.
6. The sensitivity analysis indicates that the 5h minimum operating time simulations had slightly higher monetary values when starting by the 13kW electrical demand strategy than 3h or 4h simulations.

The current strategy being implemented on the farm is that starting when the hot water storage temperature drops below 43°C. The process controller has generally worked well with few control problems. Corrosion of transducers and relays has been the most common problem. The worst failure occurred when a relay failed and excessive heating of the digester occurred, resulting in near destruction of the methane-producing bacteria.

References

- BUNDY, D.S., DVORAK, R.E. and MANGOLD, D.W. (1982). Utilizing a microcomputer for controlling the environmental systems in a swine farrowing building. In *Proceedings, Second International Livestock Environment Symposium*. American Society of Agricultural Engineers, St Joseph, Michigan
- MITCHELL, B.W. and DURY, L.N. (1980). 'Microcomputer and conventional solid state

controls for a solar heating system.' ASAE Paper No. 80-1561. American Society of Agricultural Engineers, St Joseph, Michigan

PLESSING, J.E. (1984). 'Feasibility of computer-aided environmental control in a farrowing facility.' MS Thesis, University of Nebraska-Lincoln

SIEBENMORGEN, J.J. (1984). 'Integration of a cogeneration system into a swine operation.' PhD Thesis, University of Nebraska-Lincoln

THE COMPUTER AS AN AID IN FEEDING SOWS IN GESTATION AND IN MONITORING PRODUCTION

ANNE-CHARLOTTE BENGTTSSON, JØRGEN SVENDSEN and MATS ANDERSSON

Swedish University of Agricultural Sciences, Lund, Sweden

Introduction

Development in computer technology is very rapid, and interest in the use of this technology in agriculture is also increasing. Possible areas of application are many in animal houses: for control of machinery and other equipment; to measure and control various processes; and to help the farmer with production control, accounts and analysis.

In this chapter we present a report of how a computer may be used to control and monitor the feeding of a housed group of gestating sows, which are loose in a pen, and how a computer may be used to simplify and improve the planning of work routines and the monitoring of production in a sow herd.

Use of a computer for the distribution of feed to gestating sows housed loose in groups

At the Swedish University of Agricultural Sciences (Department of Farm Buildings, Lund), a project has been in progress for several years in which, among other things, different housing systems for sows in gestation have been studied. These studies have shown that, with respect to behaviour and production, it is preferable to house gestating sows loose in groups, but this results in practical problems with feeding and individual examination of the animals (Bengtsson, Svendsen and Persson, 1983; Svendsen and Bengtsson, 1983). Therefore, a housing system is now under study in which loose-housed sows are individually fed using a computer-controlled feeding system (Alfa-Feed, Sweden) with one feeding station per group.

In this system, the sows are fitted with a neck collar having an attached sensor, or transponder. Each transponder has a unique code, corresponding to the number of the animal. These transponders have no internal power source, but when a sow places her head in the manger of the feeding stall, the transponder is energized by a coil around the feeding trough and starts to transmit. The identification signal is picked up by the receiving aerial in the feeding station, amplified in the interrogator, and sent to the processor where it is decoded. The processor then checks if there is any feed available for that sow in her daily ration. If so, it starts

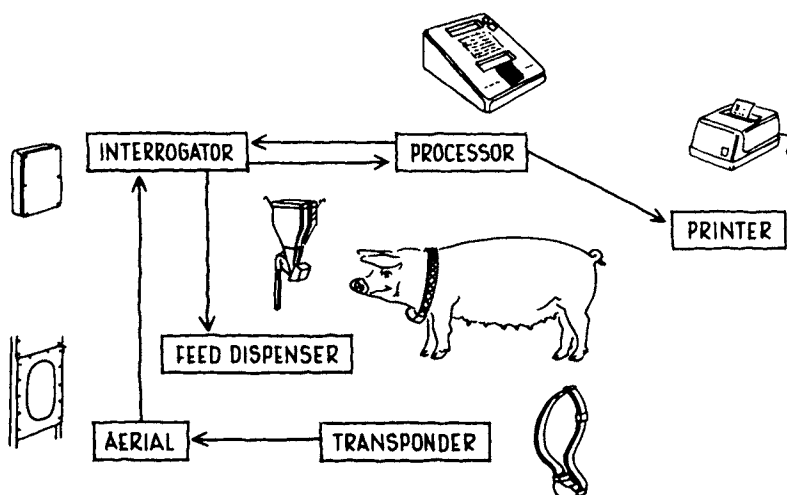


Figure 21.1 Diagram showing the different components involved in computerization of individual feeding group-housed sows in gestation

the dispenser by sending a signal to the interrogator which controls the electric motor of the feed dispenser (*Figure 21.1*).

Feed will be dispensed as long as a sow with available feed is standing in the feed station, or until the feed ration has been dispensed. It will stop if the sow leaves the station before the feed ration is finished. An auger which turns at an electronically controlled speed dispenses the feed. Its speed can be varied between 0 and 450 g min⁻¹.

The system using computer-controlled feeding has previously been used for cows but not for sows. At the Department, the cow feeding stall has been modified to fit sows and fitted with a mechanical gate system which the sow 'closes' herself when she enters the stall so that she is protected from the other sows while she is eating. In addition, the stall has been provided with a 'front gate' which enables the sow to leave the stall at the front after finishing. Thus, sows do not have to back out after using the feeding stall. This is important because behaviour studies revealed that problems occur with sows having weak legs or with aggressive animals if the sows are only able to back out of the feeding stall (Andersson, Svendsen and Bengtsson, 1984). The sows used this front gate on about 80% of the visits to the station.

The computer notes automatically the daily feed consumption of each individual sow. By precisely monitoring deviations from a normal feed consumption, possible disturbances in the animals or in the equipment can be detected early. The availability of individual distribution of feed and control of intake permits adjustment in the feed ration to even out the growth and condition of sows within groups.

With respect to the equipment, until now the system has functioned very well. The transponders may occasionally stop functioning, but this has happened very rarely during the 1½ years the system has been in use. The sows quickly learn how to use the system, especially in the small groups of 8–16 sows.

Since the sows gain 38–40 kg during the gestation period, the transponder neck collar must be checked and adjusted two or three times during the pregnancy period so that injuries do not occur. When adjusted properly injuries are very rare,

but it is impossible to guarantee that a similar adjustment can be made in all possible situations. Development of a smaller transponder, which does not have to be attached to a neck collar but can, for example, be attached to a standard ear tag, is therefore in progress. A smaller transponder is also necessary if the transponder-controlled feeding system is to be used in slaughter-pig production.

It should be emphasized that validation of the technique and its function alone is not sufficient when introducing computer control of the various systems in animal production. Computerization has no intrinsic worth; its adoption should offer improvements, which must then be evaluated with respect to their effect on the animals.

When assessing computer control of feeding for sows in gestation it is, for example, important to determine how the animals, which have in the past been fed in groups and all at the same time, will react to being suddenly forced to eat one at a time. The design of the pen and the number of sows per pen (size of group) are other parameters which may affect the functioning of the system and therefore must also be studied. If 'wrong recommendations' are given when a new technique is introduced, there is a risk that instead of solving existing problems, a number of new ones are created.

However, it can be difficult to find suitable parameters which reflect objectively how an animal experiences its environment. At the Department of Farm Buildings we have chosen to study animal behaviour, production results, and the morbidity/mortality of sow and offspring for evaluating the effect of a new technique.

Use of a computer to monitor production results

In order to simplify the collection of production data, including that from feeding sows equipped with transponders, and to improve the monitoring and directing of the production in the research herd, it was necessary to have available a computer with appropriate software. A survey showed that the number of available programs was very limited, and that they appeared to be still in the initial stages of development. With this in mind, it was decided within the Department to develop our own farm computer program to receive, store, analyse and present production data for the sow herd (Bengtsson, Pinzke and Svendsen, 1984).

This farm-data pig production program (GRISCTS) is built up of an input and an output section (*Figure 21.2*). The input section contains the subroutines used to simplify and control the recording of data. The incoming data are stored in an intermediate storage memory until collection is completed and the accuracy of the information checked, and then they are transferred to a data base for storage. The output section of the program contains subroutines for producing various types of summaries, such as work lists for helping with the daily routine and production summaries which enable the stockmen and/or owner to maintain good control over the production situations at all times. When one of the result summaries is chosen, the program retrieves the necessary information from the data base, analyses it, and presents the summary either on the screen or the printer or both, as instructed.

The program was designed for the collection of data on a day-to-day basis. Therefore, the information entered in the computer will represent the actual situation in the herd on a particular day. However, in order for the continual

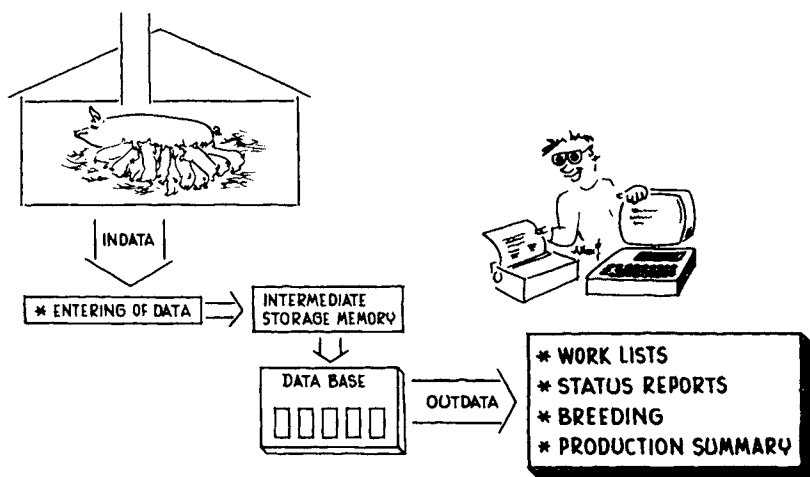


Figure 21.2 Diagram of the data flow in the pig production computer program

entering of data to function, a quick and efficient system for obtaining the required data is necessary.

For production statistics, data entry may be done either from lists or other written information, or by using a small, portable (hand-held) terminal (Olsson, 1983). If lists are to be used, the system of data recording must be adapted to the form in which the data are to be entered in the computer. If the lists are to be returned to the house for further additions, a space must be available to note which data have been entered into the computer. This type of system may lead to a management problem and a certain amount of double entering, since the information must first be noted on paper and then entered into the computer. However, if lists are returned to the house immediately after entering the current data, both the data base and the animal house will always contain current information about each animal, which can be an advantage. In addition, this type of system does not require any special equipment, and is therefore inexpensive.

If portable hand-held terminals are used, it is imperative to have a safe way of securing the original information. This may be done either by entering the information into the terminal directly, and then producing printed output, or by first noting the information on a list, as above, and then entering it on the terminal. Programs are available which can, to a certain extent, check the accuracy of the incoming information before it is sent to the herd data base. However, at the present time, the portable terminals available are relatively expensive, very few are small enough to be hand-held and, of those that are, relatively few are suited to the environment of the animal house.

At the Department of Farm Buildings, we are at present using a list system for the collection of data, because we have been unable to find a suitable portable hand terminal for testing. It should be emphasized, however, that irrespective of the method used, the output can never be more accurate than the input. Therefore, it is important to use the appropriate routines, and to be accurate when collecting and entering data.

Future research plans

At the present time in this project, two different computers are in use. One is used to control the transponder feeding program, and the other is used for the farm production program. However, it is intended in the near future to interface these two computers so that information can be transferred between them. For example, information on the service date for a sow entered in the production program can be used to control an automatic increase in the feed ration during the gestation period, via the feeding program. A second area for development will be the use of a sensor to measure temperature and heart rate in combination with the transponder for identification. This would permit monitoring the health of the individual animals, thus permitting early detection and treatment of illness and, possibly, the detection of oestrus.

Concluding remarks

The introduction of computer technology in animal production permits the housing of animals under more suitable conditions; in this case, loose housing without losing the possibility of individual monitoring and treatment. However, reliable operation is essential even in adverse conditions.

At the present, the number of computers which can stand the stresses of the farm environment, such as dust and rodents, and the number of usable programs suitable for the use of farm personnel are relatively limited. Therefore, further development is necessary for the computer to have a more general use within agriculture. Development must take place through cooperation between both farmers and biologists, so that products may be produced which are needed in agriculture, avoiding 'biological' errors which have occurred in the past with the introduction of new techniques. In addition, impartial investigations are necessary to assess the advantages and disadvantages of both the computer control and associated husbandry techniques being studied with respect to efficiency and their effects on the animals.

References

- ALFA LAVAL, ALFA-FEED DUAL INSTRUCTION BOOK. Alfa-Feed, Sweden
- ANDERSSON, M., SVENDSEN, J. and BENGTSOON, A.-C. (1984). Individual feeding using an electronic system for group housed sows in gestation. In *Proceedings, 35th Annual Meeting of the EAAP*. The Hague, European Association for Animal Production
- BENGTSOON, A.-C., PINZKE, S. and SVENDSEN, J. (1984). GRISCTS—a farm computer program for piglet production. *Swedish University of Agricultural Sciences, Department of Farm Buildings, Report*, No. 40
- BENGTSOON, A.-C., SVENDSEN, J. and PERSSON, G. (1983). Comparison of four types of housing for sows in gestation: behaviour studies and hygiene studies. *Swedish University of Agricultural Sciences, Department of Farm Buildings, Report*, No. 36

- OLSSON, L. (1983). The Farm computer—information processing. Methods for gathering, input, transfer and storage of data. *Swedish University of Agricultural Sciences, Department of Agricultural Engineering, Report, No. 90*
- SVENDSEN, J. and BENGTTSSON, A.-C. (1983). Housing of sows in gestation. Proceedings, Guelph Pork Symposium, April 1983

LIST OF POSTER PRESENTATIONS

The original intention of the editors was to include short poster papers as part of the proceedings. Unfortunately this has proved impossible within the space available. However, copies of poster papers submitted will be supplied on request.

Computer model of straw-based housing systems – an aid for agricultural advisors

T.J. Sharples

ADAS, Ministry of Agriculture, Fisheries and Food, Government Buildings, Coley Park, Reading.

Onion drying – automatic control

D.I. Bartlett and A.B. Parkin

ADAS Liaison Unit, NIAE Wrest Park, Silsoe, Bedford MK45 4HS.

Controlled environment glasshouses

S.C. Brown, P.J. Gregory and C. Vincent

Department of Soil Science, Reading University, London Road, Reading.

Glasshouse automation at Rothamsted

Julian Franklin

Rothamsted Experimental Station, Harpenden, Herts. AL5 2JQ.

The environmental monitoring and control for a solar drying barn

Elisabeth Duncan and Ron Fisher

Scottish Institute of Agricultural Engineering, Bush Estate, Penicuik, Midlothian, EH26 0PH.

Control of atmospheric humidity in a closed-circuit wind-tunnel using a low-cost microcomputer

F.C. Abreu, Q.A. Hamdi, Zheng Dawei and J.A. Clark

Department of Physiology and Environmental Science, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD.

Areal variations in heat flux densities above crop surfaces

P.N. Schaare

Department of Physiology and Environmental Science, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD.

Computer controlled heating of two small chambers connected to a BBC micro—a teaching aid

J. Craigon, K. Gregson and P.N. Schaare

Department of Physiology and Environmental Science, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD.

LIST OF PARTICIPANTS

Al-Hadi, S.S.	Department of Botany, The University, Manchester, M13 9PL, UK.
Albutt, R.W.	MAFF, Block A, Government Offices, Coley Park, Reading, RG1 6DT, UK.
Andersson, M.	Swedish University of Agricultural Sciences, Box 524, 22006 Lund, Sweden.
Atherton, J.G.	Department of Agriculture and Horticulture, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Back, H.L.	Biometry Unit, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Bailey, B.J.	NAIE, Wrest Park, Silsoe, Bedford, MK45 4HS, UK.
Bain, C.W.	Scottish Farm Buildings Investigation Unit, Craibstone, Bucksburn, Aberdeen, AB2 9TR, Scotland.
Baker, C.K.	University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Bates, B.J.	USDA ARS South Central Poultry Research Laboratory, PO Box 5367, Mississippi 39762-5367, USA.
Behzadi, M.A.	Department of Environmental Science, University of Lancaster LA1 4YQ, UK.
Belyavin, C.G.	Harper Adams Poultry Husbandry Experimental Unit, Edgmond, Newport, Shropshire, TF10 8HY, UK.
Bengtsson, A.-C.	Swedish University of Agricultural Sciences, Box 624, 22006 Lund, Sweden.
Berry, R.	Department of Physiology and Environmental Science, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Bertlett, D.	ADAS Liaison Unit, Wrest Park, Silsoe, Bedford, MK45 4HS, UK.
Blackburn, W.	Forestry Commission, Northern Research Station, Bush Estate, Roslin, Midlothian, Scotland.
Boon, C.R.	NIAE, Wrest Park, Silsoe, Bedford MK45 4HS, UK.
Brown, C.R.	Department of Soil Science, Reading University, London Road, Reading, Berks, RG1 5AQ, UK.
Buckingham, J.F.	Farm Building Division, North of Scotland College of Agriculture, Craibstone, Bucksburn, Aberdeen, AB5 6AJ, Scotland.
Burek, S.	Cranfield Institute of Technology, 21 Towcester Road, Blisworth, Northants, UK.

294 *List of participants*

Burnett, G.	Scottish Farm Buildings Investigation Unit, Craibstone, Bucksburn, Aberdeen, AB2 9TR, Scotland.
Burrage, S.W.	University of London, Wye College, Wye, Ashford, Kent, UK.
Carr-West, M.St.J.	Writtle Agricultural College, Writtle, Chelmsford, Essex, UK.
Charles, D.R.	MAFF/ADAS, Block 7, Chalfont Drive, Nottingham, NG8 3SN, UK.
Cherry, P.	Cherry Valley Farms Ltd, Divisional Offices, North Kelsey Moor, Lincoln, LN7 6HH, UK.
Chotai, A.	Department of Environmental Science, University of Lancaster, Lancaster LA1 4YQ, UK.
Clark, J.A.	Department of Environmental Science, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Cole, J.A.	Department of Agriculture and Horticulture, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Colls, J.J.	Department of Environmental Physics, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, Leics LE12 5RD, UK.
Craigon, J.	Biometry Unit, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Cranston, D.P.	Department of Botany, The University, Manchester M13 9PL, UK.
Cuminetti, R.	PEP Department, Rothamsted Experimental Station, Harpenden, Herts, AL5 2JQ, UK.
Davis, P.F.	NIAE, Wrest Park, Silsoe, Bedford, MK45 4HS, UK.
DeShazer, J.A.	216 L.W. Chase, Department of Agricultural Engineering, University of Nebraska, Lincoln, Nebraska, 68588-0726, USA.
Drury, D.J.	Farm, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Fisher, R.	Scottish Institute of Agricultural Engineering, Bush Estate, Penicuik, Midlothian, Scotland.
Franklin, J.	Biochemistry Department, Rothamsted Experimental Station, Harpenden, Herts, AL5 2JQ UK.
Fuller, R.J.	Botany School, University of Melbourne, Parkville, Victoria 3052, Australia
Gilbert, I.R.	15 Maypole Crescent, Hainault, Ilford, Essex, UK
Gregson, K.	Biometry Unit, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Gustafsson, G.	Swedish University of Agricultural Sciences, Department of Farm Buildings, PB 624, S-22006, Lund, Sweden.
Hall, R.L.	Institute of Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, UK.
Hamdi, Q.	Department of Environmental Science, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Hargreaves, K.J.	The Moorings, Canal Foot, Ulverston, Cumbria, LA12 9EN, UK.
Harrison, G.P.	Research Department, Bernard Matthews plc, Gt Witchingham, Norwich, Norfolk, NR9 8QD, UK.

Hiley, P.G.	Nickerson Group, North Kelsey Road, Caistor, Lincoln, LN7 6HA, UK.
Hooper, A.W.	NIAE, Wrest Park, Silsoe, Bedford, MK45 4HS, UK.
Humphries, R.N.	University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Hunt, P.J.	Harper Adams Agricultural College, Newport, Shropshire, TF10 8NB, UK.
Jamieson, M.	ADAS, NIAE, Silsoe, Bedford, MK45 4HS, UK.
Julian, T.A.	Department of Botany, The University, Manchester M13 9PL, UK.
Kelsey, M.	ADAS, State Veterinary Services, NAC, Stoneleigh, Warwickshire, UK.
King, A.	MAFF/ADAS, Block 7, Chalfont Drive, Nottingham NG8 3SN, UK.
Lambert, J.R.	Professor of Agricultural Engineering, Clemson University, South Carolina, USA.
Legg, B.J.	NIAE, Wrest Park, Silsoe, Bedford, MK45 4HD, UK.
Leonard, J.J.	Department of Agricultural Engineering, University of Alberta, Edmonton, Alberta, Canada.
Lightburn, D.	Shell Research Ltd, Sittingbourne, Kent, UK.
Lott, B.D.	USDA ARS South Central Poultry Research Laboratory, PO Box 5367, Mississippi 39762-5367, USA.
Lowe, J.C.	NIAE, Wrest Park, Silsoe, Bedford, MK45 4HS, UK.
McArthur, A.J.	Department of Environmental Science, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
McQuitty, J.B.	Department of Agricultural Engineering, University of Alberta, Edmonton, Alberta, Canada.
Marchant, J.A.	NIAE, Wrest Park, Silsoe, Bedford MK45 4HS, UK.
Matthews, R.B.	ODA Unit, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Meyer, C.P.	Botany School, University of Melbourne, Parkville, Victoria 3052, Australia.
Mitchell, J.R.	Applied Biochemistry and Food Science, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Nellist, M.E.	Crop Drying and Ventilation Group, NIAE, Wrest Park, Silsoe, Bedford MK45 4HS, UK.
Newton, P.	Department of Botany, The University, Manchester M13 9PL, UK.
Owen, J.E.	Department of Agriculture, University of Reading, Earley Gate, Reading, RG6 2AT, UK.
Parkin, A.B.	ADAS Liaison Unit, NIAE, Silsoe, Bedford, MK45 4HS, UK.
Parkinson, K.J.	Rothamsted Experimental Station, Harpenden, Herts, UK.
Plessing, J.E.	Department of Agricultural Engineering, University of Nebraska, Lincoln, Nebraska 68588-0726, USA.
Reece, F.N.	USDA ARS South Central Poultry Research Laboratory, PO Box 5367, Mississippi 39762-5367, USA.
Robinson, H.	Harper Adams Agricultural College, Newport, Shropshire, TF10 8NB, UK.

296 *List of participants*

Rowell, T.A.	Department of Environmental Science, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Saffell, R.A.	Campbell Scientific Ltd, College Road, Sutton Bonington, Loughborough, LE12 5RA, UK.
Schaare, P.N.	Department of Environmental Science, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Schulte, D.D.	Department of Agricultural Engineering, University of Nebraska, Lincoln, Nebraska 68588-0726, USA.
Seaton, G.	University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Sharples, T.J.	Farm Buildings Group, MAFF, Block B, Government Buildings, Coley Park, Reading, Berks, UK
Siebenmorgen, T.J.	Department of Agricultural Engineering, University of Nebraska, Lincoln, Nebraska 68528-0726, USA.
Smith, A.T.	ADAS, Woodthorne, Wolverhampton, UK
Steele, D.J.	555 Chessington Road, West Emell, Surrey, UK.
Stoddard, A.	North Western Electricity Board, Cheetwood Road, Manchester, M8 8BA, UK.
Sutcliffe, N.A.	MAFF/ADAS, Block 7, Chalfont Drive, Nottingham, NG8 3SN, UK.
Svensden, L.	Swedish University of Agricultural Sciences, Department of Farm Buildings, Box 624, S-22006 Lund, Sweden.
Tetlow, M.D.	Department of Agriculture and Horticulture, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Udink ten Cate, A.J.	Department of Computer Science, Agriculture University, Hollandsweg 1, 6706 KN Wageningen, Netherlands.
Van Wicklen, G.L.	Driftmier Engineering Center, Agricultural Engineering Department, University of Georgia, Athens, Georgia 30602, USA.
Walton, D.M.	Farm Management, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Watt, C.D.	Silsoe College, Silsoe, Bedford, UK.
Webster, S.	University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Whitfield, R.D.	NIAE, Wrest Park, Silsoe, Bedford MK45 4HS, UK.
Wilton, B.	Department of Agriculture and Horticulture, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.
Worley, J.W.	Agricultural Engineering Department, University of Georgia, Athens, Georgia 30602, USA.
Wright, C.J.	PEP Department, Rothamsted Experimental Station, Harpenden, Herts, UK.
Young, P.C.	Department of Environmental Science, University of Lancaster, Lancaster, LA1 4YQ, UK.
Zheng, Dawei	Department of Environmental Science, University of Nottingham School of Agriculture, Sutton Bonington, Loughborough, LE12 5RD, UK.

INDEX

- 3D Inlab system, 50
- Actuating signal, 232
- Actuator, 12, 234, 270
- Actuator setting, 2
- Adaptive algorithm, 77, 80
- Adaptive control, 177
- Adaptive system, 33
- Address bus, 120–122
- Adsorption hygrometer, 119
- ADZ (aggregated dead-zone) residence time, 26
- ADZ volume, 26
- Aeration, 119
- Aerodynamic resistance, 45, 53
- Aerosol, 174
- Air
 - cleaning, 244
 - contaminant, 181, *see also* Pollutant exchange, 111, *see also* Ventilation flow, 263
 - pattern, 251
 - rate, 107, 228, 253
 - mixing, 212
 - pollutant, 143
 - quality, 175, 238
 - sample, 223
 - temperature, 117, 127, 263
 - measurement, 65
 - variation, 188
 - velocity, 116, 117, 240
- Alarm, 69, 241
- Alarm condition, 170
- Algorithm, 1, 16, 77, 120, 124, 242
- Alternative energy, 265
- Ambient air, 117
- Ambient concentration (sulphur dioxide), 144, 151
- Ambient temperature, 133
- Ammonia, 174, 204, 219
 - concentration, 225
 - limit, 181
 - probe, 220, 222
 - accuracy, 227
 - calibration, 220
- Ammonia sensor, 182
- Analogue input, 122, 259
- Analogue-to-digital converter, 49, 64, 86, 200, 259, 269
 - resolution of, 179
- Animal behaviour, 287
- Animal growth algorithm, 242
- Animal health, 174
 - dust effect on, 175
- Animal housing environment, 173, 174
- Animal identification, 235, 243
- Anti-wind-up procedure, 16
- Aspirated psychrometer, 49
- Atmospheric ammonia, measurement, 221
- Automation, 235
- Autorecursive filter, 50
- Average height, 6
- AWS (automatic weather station), 48
- Balance interface, 48
- Band setting, 69
- BASIC, 61, 86, 233, 267
- Batch drying, 118
- Batch weighing, 241
- Biogas, availability, 282
 - collection, 279
 - storage, 279
- Biological optima, financial consequences of
 - deviations from, 207
- Birth detection, 236
- Broiler chicken, 199, 210, 219, 240, 244
- Broiler house, 182
 - ventilation, computer control, 187
- Broilers, fluctuating temperature for, 210
- Brooding, 199
- Brooding energy requirement, 190
- Bulk-storage drier, 129
- Canning, 159
- Capacitance determination, soil water content, 57

298 Index

- Capacitance sensor, 58
 - calibration of, 60
 - Carbon dioxide, 14, 66, 85, 174
 - injection, 87
 - Catchment tank dynamic behaviour, 29
 - Central computer controller, 77, 87, 89
 - Channel transfer function, 27
 - Channel transport delay, 36
 - Clock, 76, 86
 - Cluster, removal and attachment, 237
 - Coarse control actuation interval, 37
 - Cogenerated energy, monetary value, 283
 - Cogeneration, 265, 275, 280
 - biogas-fuelled, 279
 - Cogenerator starting strategy, 282
 - Collection efficiency, 97
 - Collector capacitance, 104
 - Collector performance, 103, 111
 - Collector, temperature rise through, 97
 - Communication, 78
 - Computer
 - Commodore 64, 190, 200
 - Commodore VIC-20, 200
 - Control
 - benefit of, 170
 - feasability, 183
 - strategy of, 63, 173, 178, 265, 281
 - IBM PC, 122, 266
 - low-cost, 199
 - Texas Instruments, 74
- Computer-controlled feeding, 285
 - Computer interface, *see* Interface
 - Computer model, 166
 - Computer simulation, 23, 127, 166, 182
 - Concentration frequency, 144
 - Connection diagram, 202
 - Continuous weigher, 242
 - Continuous-flow drying, 118
 - Control
 - actuator, 64
 - air inlet speed, 239
 - air temperature, *see* Temperature control
 - algorithm, 17, 140, 169, 180, 193, 240, 252
 - analysis, 6, 38
 - bus, 120–122
 - closed-loop, 231
 - constraint, 37
 - conventional, 177, 256, 271
 - equipment, 223
 - loop, 14
 - stability, 232
 - of floor temperature, 271
 - operation, 69
 - performance, 41
 - problem, 110
 - program, 188, 194
 - replicate, 233
 - requirement, 99
 - room temperature, *see* Temperature control
 - self-tuning, 33
 - sensitivity, 139
 - Control (*cont.*)
 - setting, 263
 - software, *see* Software
 - stability, 232
 - strategy, 99, 135, 180, 239, 282
 - system, 14, 176, 241, 268, *see also* Computer control
 - action of, 231
 - classification, 232
 - design, 32
 - performance, 38
 - theory, 231
 - time-proportioning, 203
 - using lower critical temperature, 255
 - Controllability, regression analysis of, 208
 - zone of, 208
 - Controlled environment housing, 219, *see also* Animal housing
 - Controller, conventional, 64
 - Controller interface, *see* Interface
 - Controller malfunction, 89
 - Conventional control, 177, 256, 271
 - Cooking, 165
 - Cooking/sterilization, 161
 - Cooling, 100, 165
 - Correcting action, 232
 - CPU (central processor unit), 121, 180, 266
 - Critical temperature, 175
 - lower, 237, 251, 253, 256
 - upper, 237, 251
 - Crop drying, 95, 110, 115
 - environment, 115
 - Cross-flow drier, 131
 - Cycle time, 203
-
- Dairy cow, 243
 - Dairy management, 235
 - Data
 - acquisition, 24, 213, *see also* Data logger
 - base, 287
 - bus, 120, 121, 122
 - collection, 70, 269
 - display, 212
 - logger, 1, 48, 61, 73, 85, 190, 211, 223, 256, 261
 - printout, 91
 - storage, 78, 261
 - transmission, 169
 - DDC system, 33, 37
 - Dead band, 203
 - Dead time, 8, 16
 - Dead-beat behaviour, 33
 - De-bugging, 246
 - Dedicated system, 163, 166
 - Derived value control, 166
 - Desired temperature, *see also* Set temperature, 189
 - Dew point temperature, 124
 - Differential pressure transducer, 269

- Digester, 275
 - heating requirement, 281
- Digital input, 68, 269
- Digital-to-analogue converter, 86
- Direct control, 163
- Discrete control, 239
- Discrete proportional plus integral (PI) controller, 16
- Discrete time, 16
- Dispersion, Gaussian, 146
- Display, 164
- Distributed control, 169
- Distributed system, 63, 73, 85
- Diurnal uptake distribution, 31
- Documentation capability, 170
- Dose accumulation (SO_2), 157
- Dräger sampling tube, 219, 225
- Drier
 - behaviour of, 127
 - control, 134, 140
 - strategy, 135
 - throughput, 133
- Dry feed, 242
- Dry-bulb temperature, 115, 124, 207
- Drying, 95, *see also* Crop drying and Driers
 - air temperature, 133, 135
 - constant, 128
 - grain, 96
 - process, modelling of, 128
 - rate, 99, 116, 128
- Dust problem, 244
- Dynamic behaviour, 4
- Dynamic characteristic, 33

- Economic result, 283
- Electrical demand, 282
 - profile, 278
- Electrical load, 276, 278
- Electrical noise, 179
- Electromagnetic interference, 245, *see also* Noise
- Electronic balance, Satorius 3806MP, 46
- Electronic control, problem, 245
- Enclosure, 245
- Energy
 - conservation, 1
 - consumption, 187, 272
 - input, 272, 274
 - saving, 237
 - use, 181, 183, 275
- Energy integrated farm, 282
- Environmental control, 63, 237, 268
- EPROM, 63, 75, 77, 86, 200, 233, 259, 260
- Error budget, 226
- Error signal, 176, 232
- Evaporation, 48
- Evaporation flux from wet vegetation, 45
- Exhaust air temperature, 135
- Expansion port, 200
- Exposure system, 144

- Fail-safe, 239, 241, 275
 - ventilation, 180
- Fan speed control, 238
- Farmstead energy demand, 275, *see also* Energy use
- Fast Fourier transform, 2
- Feed
 - delivery, 241
 - distribution, 285
 - metering, 241
 - proportioning, 241
- Feed-forward
 - compensation, 17
 - control, 135, 177
- Feedback, 66, 231
 - control, 136, 176
 - loop, 139
- Feeding, 241
 - level, 253
 - system, 242
- Field fumigation system, 143
- Finishing pig, 251
- Finishing piggery, 257
- Fixed-gain control, 35
- Flame photometric sulphur analyser, Meloy SA285, 149
- Floor heating system, 267
- Floor insulation, 253
- Flow chart, microprocessor retort control, 162
- Flow diagram, 189, 268, 288
- FORTRAN, 77, 233
- FPC, fully programmable control, 234
- Frequency domain analysis, 2
- Fruit drying, 95
- Fuel use, 205
- Fuel, methane gas, 265
- Fumigation, 144
 - dose, 155
 - period, 155
 - system, 144
 - performance, 149, 151

- Gas
 - analysis, 87
 - concentration, 174, 181
 - cost, 188
 - mixture, 146
- GCFFC (greenhouse climate feedback/feedforward control), 2–5, 9, 14
 - behaviour, 15
- Glasshouse, 63, *see also* Greenhouse
 - computer-controlled, 64, 68
 - control, 86
 - environment, 63
 - industry, 63
- Grain
 - aeration system, 123
 - drier, computer model of, 137
 - output moisture content, 134

300 Index

- Grain (*cont.*)
 - drying, 128
 - commercial system for, 123
 - computer simulation of, 127
 - control of, 127
 - throughput, 134
 - flow rate, 135
 - moisture content, 123
 - quality, 130
 - temperature, 132
 - viability, 130
- Greenhouse, 73, 96, *see also* Glasshouse
 - air temperature, 9, 108
 - climate control, 1, 32
 - control, 100
 - environment, computer control, 73
 - heating, 98
 - temperature, 101, 106, 107, 110
 - control, 14, 49
- Group size, pigs, 253
- Hand-held terminal, 288
- Handshaking, 87, 91
- Health, 243
- Heat
 - balance, 252
 - collection, 101
 - consumption, 132, *see also* Energy
 - exchange, 237
 - loss, 273
 - production, thermoneutral, 252
 - requirement, 182
 - sterilization, 161
 - store, 97
 - transfer, mathematical model of, 166
- Heated air drying, 116, 129, 130
- Heater, 188
- Heating, 100
 - control, 183
 - cost, 240
 - pipe network heating capacity, 13
 - system, 4, 188, 193
 - control, 15
 - thermal loss, 195
- Heating-ventilation interlock, 182
- Herd data base, 288
- Herd management, 235
- High-frequency signal component, 9
- High-level language, 81
- Host computer, 63
- Hot water
 - demand, 282
 - storage, 281
- House heat balance, 207, 210
- House temperature, 215, 219
- Humidistat, 177
- Humidity, 65, 85
 - control, 65, 86, 89, 110, 203, 204
 - desired, 92
 - measurement, 66, 88
- Hunting, 101
 - control of, 104
- Hydrogen sulphide, 174
- Identification signal, 285
- IEEE 488 bus, 50
- Incident radiation, 103
- Individual feeding, 235, 243
- Infra-red gas analyser, 66, 88
- Inlet air speed, 255, *see also* Air velocity
- Input moisture content, 133
- Input/output, 47, 56, 232, 262
- Instability, 232
- Installation problem, 183
- Intercepted precipitation, 45
- Interception loss, 45
- Interface, 75, 122, 190, 202, 269
 - RS232, 86, 87
- Interfacing, 68, 119, 123, 182, 266
- Interrupt, 78
 - line, 91
- Interval timer, 122
- Investment, return of, 173
- Ion selective electrode system, 22, 41
- Kiln drying, timber, 96
- Ladder diagram programming, 266
- Latent heat, 203
 - flux, 52, *see also* Evaporation
 - (moisture) production, 199
- Layer, 210
- Learning procedure, 33
- Line source, sulphur dioxide, 144
- Linear modelling, 2
- Linear, quadratic, gaussian (LQG) feedback system, 41
- Liquid crystal display, 259
- Liquid feed, 242
- Litter, 199
- Livestock
 - building, electronic control, 231
 - housing, 234
- Load management, 265
- Look-up table, 90
- Low-pass filter, 50
- Low-temperature drying, 96
 - grain, 124
- Machine-code, 234
- Master-slave control, 15
- Menu, task, 234
- Meteorological sensor, 46
- Methane, 174
- Microclimate measurement, 80
- Microclimatology, 85

- Microcomputer, 222, 256
 - board, Arcom ARC1, 86
 - Epson HX-20, 24
 - low-cost, 199
 - Motorola 6800, 163
 - personal, 180
 - Pet 4032, 46
 - single board, 74
 - Texas Instruments TN 990, 74
- Microprocessor, 174, 180
 - control, 85, 188, 233, 240, 251, 257
 - 6510, 200
 - 6809, 259
 - MC6809, 189
 - TM 9900, 74
 - Z80A, 222
- Milk
 - flow, 236
 - quality, 236
 - yield, 236
- Minimum drying rate, 123
- Mixed-flow drier, 133
- Mixing valve, 12
- Model
 - ADZ (aggregated dead-zone), 25, 29
 - combined GCFFC, 11
 - control, 1, 2, 24
 - detailed simulation, 41
 - GCFFC, 14, 18
 - 'general', 3, 14
 - GCFFC, 4, 6, 17, 18
 - nutrient delivery system, 23
 - perturbation, 3, 4, 10, 18
 - physical, 1, 9
 - time-series, 26
- Modelling, control, 183
- Modem, 267
- Moisture
 - content, 117, 128, 133
 - control, 181
- Morbidity/mortality, 287
- MPP (microprocessor Pascal), 75, 77
- Multiple function control, 234
- Multiple temperature sensing, 239
- Multiplexer, 49, 61, 62, 75, 269
- Multiplexing, 200
- Net radiation, 52
- Network, 74, 81
- NFT (nutrient film technique), 21, 41, 67
 - control model, 23
 - system, dynamic behaviour of, 24
- Noise, 50, 245
- Non-linearly saturated, 14
- Non-thermal environment, 174
- Nutrient
 - concentration, 26, 93
 - delivery system, 24
 - flow, 77
 - solution, 21
 - conductivity, 22
 - uptake, 31, 38
- Oestrus detection, 236
- On-time, 203
- On/off control, 22, 99, 136, 176
- Open top chamber, 143
- Operational mode, 100
- Operator
 - facilities, 91
 - interface, 266
 - problem, 246
- Optimal drying, 99, 117
- Optimum broiler performance, 200
- Optimum drying temperature, 99, 124
- Oscillation, control, 136, *see also* Hunting
- Output, 68, 123, 182
- Over-drying, 117
- Overshoot, 14
- Parallel-flow drier, 130
- Pascal, 77
- Penman-Monteith equation, 45
- Performance characteristic, 14
- Perturbation, 1, 3, 14
 - high-frequency, 9
 - parameter, 11
- Phase shift, 232
- Photosynthesis, 87
- PI (proportional plus integral)
 - algorithm, 16
 - control, 37
 - controller, 16
- PID (proportional, integral and derivative)
 - control, 176, 181
- Pig, 175, 182, 240, 244
 - lower critical temperature, 240
 - production program, farm-data, 287
- Piggery, 251
 - temperature, 263, 264
- Platinum resistance thermometer, 49, 164
- PLC (programmable logical controller), 2
- Pollutant concentration, 143, 181
- Pollutant gas, safe limit, 175
- Portable terminal, 288
- Position control, 17
- Position indicator, 66
- Positive feedback, 35
- Poultry, 175, 181, 242
 - brooding, 239
 - solar heated, 182
 - building, 219
 - response model, 207
- Poultry house
 - environment, 207
 - control, 182, 199, 201
 - poor control, 214
- Power consumption, 241
- Power supply problem, 180
- Pregnancy detection, 236
- Presence detection, 235
- Pressure measurement, 269
- Pressure transducer, 164
- Print-out, 70, 91

- Probe position, 213
- Process control, 265
- Process cycle, 166
- Process optimization, 168
- Processing condition, 165
- Processing variable, 167
- Product temperature, 164
- Product variable, 168
- Production, 287
 - monitoring, 285
 - record, 235
- Program
 - development, 88
 - terminal, 266
 - flowchart, 51
 - storage, 200
 - structure, 88
 - subroutine, 287
- Programmable controller, 99, 166
- Proportional band, 203
- Proportional control, 66, 69, 137, 138, 176
 - stepped, 177
- Proportional plus integral algorithm, 77, 80
- Proportional plus integral control, 137, 138
- Proportional plus rate algorithm, 76
- Psychrometer, 65, 88
- Psychrometric chart, 123
- Psychrometric diagram, 116
- Public safety regulation, 161
- Pumping time, 224
- Pure time delay, 31
- PVC pipe brooder, simulation model, 194

- Radiation flux density, 6
- Rainfall interception, 45
- RAM, random access memory, 233
- Relative humidity, 181, 199
- Reliability, 245
- Replicate control, 233
- Required temperature, 199
- Residence time, 28, 31
- Resistance block, 58
- Resistance thermometer, 119
- Response speed, 176
- Response time, 183
- Retort, 163, 168
 - control, 163
 - temperature, 169
- Robust control algorithm, 140
- Rockpile, 104
 - charging, 100
 - cooling potential, 110
 - discharge, 105
 - storage, 97
 - bidirectional, 98–100
 - unidirectional, 98, 107–109
 - temperature profile, 106
 - volume, 107
- Ruminant, 175

- SAC (self-adaptive control), 32
 - simulation of, 34
 - system, 23, 33
- Sag, 14
- Sampled-data control, 33
- Sampling
 - frequency, 180, 212, *see also* Scan frequency
 - interval, 7, 37
 - period, 16
- Scan
 - cycle, 151
 - frequency, 214
 - interval, 69
- Schedule-adaptive control, 32
- Security, 241
- Seed ageing, 130
- Self-tuning control, 33
- Sensible heat, 203
- Sensitivity analysis, 282
- Sensor, 64, 89, 169, 212, 232–235
 - failure, 245
 - leaf temperature, 86
 - position, 212
 - siting, 109
 - soil temperature, 86
 - solar irradiance, 86
 - technology, 71
 - time constant, 176, 180
 - temperature, 176, 178, 189, 211
- Sequencing, 234
- Serial data link, 63
- Set condition, 232
- Set floor temperature, 270
- Set point, 73, 120, 136, 176, 180, 270
- Set temperature, 92, 183, 203, 238, 261
 - variable, 240
- Signal conditioning, 123, 178, 179
- Signal line, 121
- Slave loop, 16
- Smell problem, 244
- Software, 88, 180–182, 234, 239, 246, 260
 - development, 182
 - error, 246
- Soil,
 - heat flux, 50
 - heat storage, 11
 - moisture measurement, 60
 - tensiometer, 58
 - water content, 57
- Soil-less system, 67
- Solar air
 - collector, 107
 - heating system, 96, 98
 - system
 - control, 95
 - performance, 100
- Solar
 - collector, 95, 267
 - energy, 95, 239
 - heat gain, 272
 - heating, 265, 273

- Solar (*cont.*)
 - radiation, 80
 - Sow, 285, *see also* Pig
 - Sow, feeding group housed, 286
 - Space heating, 98
 - Spatial uniformity, 144
 - Star system, 63
 - State-variable feedback pole assignment, 23, 33, 37
 - Steady state
 - control, 16
 - gain, 26, 31
 - Sterilization, 167
 - temperature, 161
 - Stevenson screen, 258
 - Stocking density, 173
 - Storage tank, thermal analysis of, 195
 - Storage temperature, 281
 - Strain gauge, 236
 - Sulphur dioxide
 - effect on barley yield, 157
 - fumigation, computer control, 143
 - Supplemental heat, 117, 175, 192
 - Surface temperature, 52
 - Swine, 265, *see also* Pig
 - Swine housing, 267
 - Switching, 182
 - System architecture, 64
 - System hardware, 258
-
- Target concentration, sulphur dioxide, 145, 149
 - Temperature, 65, 85
 - accumulated, 210
 - actual, 203
 - control, 3, 18, 86, 89, 183, 203, 207, 238, 270
 - program, 168
 - cycle, 210
 - distribution, 166, 212
 - glasshouse, 65
 - fluctuation, 210, 211
 - lift, 214, 217, 224
 - measurement, 88, 163, 200, 227, 269
 - test house, 262
 - Testing routine, 239
 - Thermal analysis, 194
 - Thermal efficiency, 194
 - Thermal energy management, 279
 - Thermal inertia, 104
 - Thermal load, 278
 - Thermal performance, 208
 - poultry house, 215
 - Thermal resistance, 5, 36
 - Thermal storage, 267
 - Thermistor, 49, 119
 - Thermocouple, 49, 119
 - Thermoelectrically cooled mirror, 119
 - Thermometer, 258, *see also* Temperature measurement
 - Thermoneutral zone, 251
 - Thermostat, 99, 177, 183
 - Time constant, 8, 10, 176
 - Time lag, 232
 - Time-proportional control, 17
 - Time-series analysis, 2
 - Timed operation, 69
 - Tiny-BASIC, 88, 90
 - Tomato, 22, 29, 81
 - nutrient uptake, 31
 - Tracer
 - experiment, 30
 - studies, 24
 - Transducer, 119, 232, 258
 - Transfer function, 6, 9, 26, 36
 - Transponder, 243, 285
 - Transport
 - delay, 25, 38
 - time lag, 6
 - Trombe wall, 268
 - Tropical climate, simulation, 85
 - Tropical crop, 85
-
- Udder washing, 235
 - Under-shoot, 14
-
- Vacuum control, 237
 - Validation, 2, 287
 - VDU (visual display unit), 69
 - Velocity controller, 17
 - Venlo greenhouse, 73–81
 - Ventilation, 6, 175, 182, 238, 257, 267, 273
 - automatically controlled natural, 216
 - computer controlled broiler house, 187
 - control, 17, 89, 183, 188
 - for CO₂, 181
 - fan, 202
 - control, 268
 - humidity control, 192
 - maximum rate, 253–257
 - minimum rate, 180–183, 219, 238, 240, 253, 255, 257
 - natural, 216
 - position, 67
 - rate, 14, 183, 199, 204, 208, 240, 261
 - requirement, 181
 - system, 187, 212, 215, 251
 - high-speed jet, 212, 217, 251–256
 - VIA (versatile interface adaptor), 47
 - Viability, loss of, 131
 - Volume measurement, 236
-
- Waste disposal, 243
 - Water
 - level, 164
 - vapour, 115
 - Weather data, 78
 - Weather station, 67, 87

304 *Index*

Weighing

animal, 244

water loss, 48

Weight measurement, 241

Wet-bulb temperature, 115

Wind

direction, 146

interference, 215

Wood furnace, 193

thermal analysis of, 195

Working environment, problems of, 245

Zero setting, 257